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THE SEDIMENTATION UNIT AND ITS USE IN FIELD SAMPLING[1]

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ABSTRACT

Four objectives of quantitative study of sediments are outlined, each of which requires specially collected samples. The corresponding techniques of collection are here called engineering sampling, descriptive sampling, environmental sampling, and correlation sampling, according to the purpose of the samples. The steps in the systematic collection of samples for the first three purposes are outlined. Certain principles underlying efficient correlation sampling are considered.

There are two techniques for environmental sampling depending on the kind of measurements to be made. Criteria are given for determining whether or not composite samples may be used. When composite samples are unsuitable, samples from individual layers are required. In the latter case, the sedimentation-unit concept furnishes a practical field tool for the rational selection of the layer or combination of layers to be sampled as a unit. An example of the use of the sedimentation unit, showing how the boundaries of the individual units are determined, is given in detail. Six general steps for the determination of a sedimentation unit are given. Devices for obtaining the samples are described.

INTRODUCTION

There is a growing recognition that the problems of field sampling are fully as important as those of laboratory technique. A rational approach to the problem of sampling would be a desirable geological tool. It is proposed to show that such an approach is possible and

[1] Published with permission of the Soil Conservation Service, U.S. Department of Agriculture.

that in many cases the sedimentation unit is a practical unit in the field sampling of sediments.

Laboratory measurements on samples of sediments are generally made for one of four purposes:

1. To determine the suitability of a deposit for economic utilization. The collecting of samples for such a study is here called *engineering sampling.*

2. To permit a detailed petrographic description of a formation or similar unit. The collecting of samples for this purpose is here called *descriptive sampling.* One or more samples may be needed. A series of systematically collected samples enables the variability or homogeneity of a stratigraphic unit to be stated quantitatively.

3. To establish a relation between measurements made on each member of a series of samples and changes in the environment of deposition. A textural variation series[2] of beach sands is an example in which changes in mechanical composition are correlated with net linear distance of travel. Likewise, for areal studies of variation sampling grids are employed to elucidate the environmental "pattern."[3] The collecting of a suite of samples suitable for this purpose is here called *environmental sampling.*

4. To establish similarities or differences between two or more sets of samples from the point of view of geological correlation. The collecting of a suite of samples for this purpose is here called *correlation sampling.*

ENGINEERING SAMPLING

Mining engineers have devoted much study to the problems of engineering sampling. Their points of view and techniques have been adopted with little modification by geologists. The modifications generally have been made with the intention of retaining the representative-sample concept without using large samples.

Engineering sampling aims to obtain average samples or representative samples. To attain this end a systematic sampling program includes the following steps: The boundaries of the deposit

[2] F. J. Pettijohn and J. D. Ridge, "A Textural Variation Series of Beach Sands from Cedar Point, Ohio," *Jour. Sed. Pet.*, Vol. II (1932), p. 76.

[3] W. C. Krumbein and Esther Aberdeen, "The Sediments of Barataria Bay," *Jour. Sed. Pet.*, Vol. VII (1937), p. 17.

are determined and the area to be sampled is divided into rational subgroups. Each subgroup is divided into arbitrary areas or unit volumes, usually according to a grid pattern, to eliminate personal bias in the sample selection. Some kind of channel sample is taken at each location. Two or more of these may be combined to form a single laboratory sample where the variability is small or where the sampling cost is notably less than the analytical cost. Each channel sample is usually a composite of many layers. The thickness of material included in a single channel sample is determined mainly by economic considerations of the actual exploitation. Only those layers are excluded which could profitably be kept separate in the commercial exploitation of the deposit.

DESCRIPTIVE SAMPLING

Descriptive sampling ordinarily involves the selection of a few typical samples from spot locations. Thus for a petrographic description of a member of a formation one sample may be selected to represent each facies Samples of conventional hand-specimen size are adequate except for coarse sediments.

However, if a quantitative measure of the homogeneity of a formation is desired, a sampling plan which reduces the personal element in the sampling is needed. A procedure analogous to that used in engineering sampling may be followed:

1. Define the lithologic units of the formation in terms of the agencies and time of deposition. If this cannot be done in the field, then subdivide the formation into relatively large or persistent lithologic units.

2. Fix the geographic limits of the investigation and apply a grid system, preferably three-dimensional, such that the number of samples is consistent with the precision required.

3. Take spot samples from each location. The sample size should be just large enough to represent adequately the rarest or coarsest component under consideration. Each major lithologic unit should be sampled separately.

4. Exclude only those samples which owe their irregularity to the work of an agency not affecting the remaining samples and not included in the investigation. Thus if a sample location determined by

the grid pattern lies in a fault zone, no sample should be taken from that location.

To shorten the laboratory work groups of four or eight adjacent samples may be combined into composite samples. The observed variability of the series of composite samples will be considerably less than the variability computed from determinations on the much larger number of component samples; a mathematical correction[4] can be applied when it is desired to compute a quantitative index of variability.

ENVIRONMENTAL SAMPLING

The development of efficient procedure for environmental sampling requires recognition of two classes of measurements made on sediments. The first class consists of such measurements as quantitative chemical and mineralogical composition, average diameter, and average sphericity.

Any measurement of this class is an arithmetic mean value of some property of all the particles in the sample, or is a ratio indicating frequency of occurrence. For these measurements the value obtained by analyzing a composite sample is the same as the value obtained by averaging separate analyses of the components. When the component samples represent unequal amounts of the composite sample, weighted averages are used.

The other class of measurements is characterized by the failure of a measurement on a composite sample to agree with the average of measurements made on the component samples. Such failure occurs when the measurement is dependent on the orientation of the individual particles. Porosity and permeability measurements in situ are examples in which the original orientations are lost in the composite sample. Measurements of dispersion of particle sizes such as quartile deviations[5] and the standard phi deviation[6] may also be misleading when made on composite samples. Thus if well-sorted

[4] W. C. Krumbein, "The Probable Error of Sampling Sediments for Mechanical Analysis," *Amer. Jour. Sci.*, Vol. XXVII (1934), pp. 204–14.

[5] W. C. Krumbein, "The Use of Quartile Measures in Describing and Comparing Sediments," *ibid.*, Vol. XXXII (1936), pp. 98–111.

[6] W. C. Krumbein, "Application of Logarithmic Moments to Size Frequency Distributions of Sediments," *Jour. Sed. Pet.*, Vol. VI (1936), p. 40.

beach sand is mixed with well-sorted gravel, the apparent sorting of the composite sample will be poor. This principle can be extended to other measurements in which the distribution of sizes and shapes is a factor, as in measurements of minimum porosity, bulk density, and angle of repose.

The data in Table 1 illustrate these two classes of measurements. Six samples were taken from a desert dune about ten miles southwest of Baker, California, at the southwestern edge of ephemeral

TABLE 1*

STATISTICS OF THE MECHANICAL ANALYSES OF THE CRONISE LAKE DUNE

Sample No.	Mean Diameter M_ϕ	Standard Deviation σ_ϕ	Median Diameter Me_ϕ	Quartile Deviation QD_ϕ	Quartiles	
					Q_1	Q_3
1	2.15	.384	2.11	0.22	2.36	1.92
2	2.47	.315	2.47	.17+	2.65	2.30
3	2.55	.294	2.57	.15+	2.72	2.41
4	2.60	.377	2.60	.20	2.80	2.40
5	2.70	.374	2.69	.20	2.90	2.50
6	2.76	.350	2.77	0.21	2.98	2.56
Average	2.54−	.349	2.53+	0.19	2.73+	2.35
Composite sample	2.54	.402	2.54	0.22+	2.77	2.32

* The phi scale of particle-size measurement is used, defined by $\phi = -\log_2(\xi)$, where ξ is the diameter of the particle in millimeters. It is especially useful when comparing sediments whose average diameter undergoes a progressive shift from sample to sample. The parameters expressed in phi units are readily adapted to mathematical analysis. Phi measures of dispersion are directly comparable because a given numerical difference signifies the same relative change in particle diameter regardless of the average diameter of the particles.

Cronise Lake. All the samples were taken from the top half-inch of one homogeneous layer. Sample 1 is from the base and Sample 6 is from the crest. One purpose of these samples was the determination of the average sorting under the conditions of deposition prevailing at the time of collection.

The parameters or statistics given in Table 1 summarize most of the information contained in the six sieve analyses. Beneath the data for the six analyses the average value for each statistic is given. The bottom line of the table gives the corresponding parameters of the average sieve analysis. This average analysis was obtained by

averaging the percentages on each sieve for the six samples. Note that the two values of M_ϕ are the same; for the other statistics, except the median, the average values are different from the values of corresponding statistics of the average sample. In general, the values of the median will be different. In the present example the mean and the median nearly coincide and thus behave similarly.

ENVIRONMENTAL SAMPLING WHEN COMPOSITE SAMPLES ARE SUITABLE

A modified engineering-sampling program is satisfactory for those environmental-sampling studies for which composite samples are suitable. The area or linear zone to be sampled requires critical definition in terms of the geological agents producing the sediment. Thus in a beach investigation devoted solely to water-deposited sand, the interbedded wind-deposited sand should be removed from the channel samples. The sampling localities are determined by a suitable grid-location system. The depth of the channel samples at each locality is determined by geological conditions such as the thickness of water-laid material deposited since a major storm or during a definite part of a tidal cycle. Samples should not be taken to a uniform depth over the entire area unless it can be shown that the deposit is uniform in thickness. Where there is considerable local variation, such as that introduced by beach cusps, composite samples of several channel samples will smooth these local irregularities and save much laboratory work. The locations of the component channel samples are best determined by a grid pattern adjusted to the scale of the local irregularities. Thus, in sampling cuspate beaches, six channel samples taken from comparable points of the arc between two beach cusps may be combined at each sampling locality. Arbitrary spacing grids are unsatisfactory because they do not take into account the differences in scale of the disturbing factors at the various sampling localities.

THE SEDIMENTATION UNIT

A sample taken from an apparently homogeneous layer of a sediment is generally composed of a number of laminae. These laminae differ somewhat in average particle diameter so that measures of dispersion for a group of laminae will be greater than the average of

the same measures for the individual laminae. To conclude that it is impractical to sample individual laminae, or to agree upon an arbitrary sample volume, is not sufficient. A rational unit for sampling is needed. The writer proposes the sedimentation unit

The sedimentation unit at any sampling point is that thickness of sediment which was deposited under essentially constant physical conditions. Chance deviations of all sedimentary characteristics about a mean value may be present; these deviations, however, should themselves constitute a unimodal distribution. The words "essentially constant" do not preclude the existence of a trend[7] in conditions. This trend may be a simple linear type or a cyclical change in conditions.

The sedimentation-unit concept has proved a valuable field tool in the sampling of various types of beaches, certain types of desert dunes, desert-stream beds, sand and gravel deposited by distributaries on alluvial fans, desert-sand accumulations around bushes, gravel terraces in a canyon, and sediments formed in a canyon by temporary ponding of the water

The sedimentation unit is more easily visualized in the field in terms of assignable and nonassignable causes of variation and their effect on the laminae of the sediment.

A lamina is the smallest recognizable unit layer of particles of a sediment. The thickness of a lamina may vary from microscopic size for clays to many inches for coarse-gravel deposits.

Nonassignable causes of variation in the characteristics of a sediment are those causes which determine the distinguishing characteristics of individual laminae; the effects of these causes are lost when measurements are made on groups of laminae. Nonassignable causes are recognized by relatively small and rapid fluctuations in their magnitude and the unpredictability of their behavior for even short-time intervals.

Assignable causes of variation in the characteristics of a sediment are those causes which affect adjacent laminae to the same extent or to a uniformly changing extent. Assignable causes of variation are recognized by the predictability of their behavior for considerable

[7] F. C. Mills defines "trend" thus, "The concept of a trend is of a regular smooth underlying movement from which there are deviations, but which marks the long-time tendency of the series" (*Statistical Methods* [Henry Holt & Co., 1924], p. 304).

time intervals, by their relatively long cycles of variation (lasting from many minutes to years, in contrast with cycles of variation lasting seconds or a few minutes as in the case of the nonassignable causes), by the property that a change in the magnitude of the cause produces effects in the composition of the sediment which can be detected by making measurements on adjacent groups of laminae.

EXAMPLES OF NONASSIGNABLE AND ASSIGNABLE CAUSES OF VARIATION AT THE CRONISE LAKE DUNE

The Cronise Lake dune mentioned previously is held in place by rock hills on the south and west and a highway fill on the north. The dune is situated at the edge of the playa near the mouth of a desert stream and extends to the top of the west rock hill. Sand is swept over the top of the hill during even moderate winds. The average grain size decreases toward the top. The individual laminae are rather indistinct but are grouped together into fairly distinct bands. At the time of the writer's visit the dune was covered with small, remarkably uniform ripple marks.

The field conditions indicate that the growth of the dune (and, consequently, the sedimentation units) is related mainly to weather conditions, principally the magnitude and direction of the wind velocity. For short periods of time in fair weather such growth factors as sand supply, moisture conditions, availability of sand, and size and shape of the dune remain virtually unchanged. The wind variations are of two kinds: the erratic local fluctuations in velocity not specifically assignable to definite causes and those larger variations assignable to definite causes. The former constitute nonassignable causes of variation and the latter assignable causes of variation in the characteristics of the dune. The concept of nonassignable causes may be explained by considering the mode of formation of a single lamina of a ripple-marked dune.

A favorable gust of wind will add a thin layer of sand to the dune. This layer will not be added as a continuous sheet one or more sand grains thick, because the sand is added to a ripple-marked surface. The ripple marks vary in mechanical composition from trough to crest. The minute eddies between each pair of ripple marks cause the newly added sand to be sorted and deposited in bands whose particle size conforms to the difference already existing in different

parts of each ripple mark. The ripple marks continually migrate and change their dimensions in response to many minor changes in magnitude and direction of the wind. During rearrangement of the ripple marks, previously deposited laminae will be shifted and mixed with other laminae. A new gust of wind will bring another load of sand. If conditions remain fairly constant, the continued addition of sand will build up the ripple marks by accretion. Layers of sand grains which formerly moved only during rapid changes in the ripple marks will now remain unmoved. The result will be a complex system of laminae, many of which are traceable for a few inches only.

Each lamina owes its distinctive characters to the many slight changes in wind magnitude and direction. These changes are unpredictable. They can be recorded, but even with such a detailed record it is not possible to assign a particular set of fluctuations to a single lamina. Each lamina is the result of a chance cause system which is not constant from one lamina to the next. If the average wind velocity and average direction of the wind remain constant, layers of thirty or more laminae will possess practically identical statistical properties. The effects of the nonassignable causes are eliminated when a number of adjacent laminae are considered as a unit, because the *chance cause system which gave rise to these layers is essentially constant.*

Two assignable causes of variation in wind velocity are movement of storm centers across the continent and diurnal temperature fluctuations which give rise to diurnal winds. In striking contrast to the fluctuations just considered, the approximate magnitude and direction of changes in wind velocity due to these causes are predictable for hours or days ahead from a weather map and a knowledge of meteorology and local conditions. Also it is possible to predict the effects of these changes on mechanical composition and bedding. These predictions are possible despite the presence of nonassignable causes of variation, because the resultant effect of the latter is essentially constant whenever layers of a considerable number of laminae are considered.

Assignable causes of variation usually undergo cyclical changes in magnitude or importance; the effects of these variations are recorded in the sediment as gradual changes in composition within otherwise homogeneous layers. These cycles of variation may last months as

in the case of changes in sand supply, or days as in the case of cyclonic winds blowing out from a high-pressure area, or hours as in the case of diurnal winds caused by diurnal temperature changes. For studies lasting only a few days or hours, the slower cyclical changes may be considered constant.

As long as the assignable causes of variation remain essentially constant or change slowly, the sediment deposited continuously during the shortest cycle of variation of these causes constitutes a sedimentation unit. However, if at some stage during the cycle of variation physical conditions undergo a definite change, such as from laminar to turbulent flow in a lake, this change marks a sedimentation-unit boundary. Also if sedimentation ceases locally or is replaced by erosion, the change records a sedimentation-unit boundary.

A series of samples taken from the same sedimentation unit at different sampling points enables regional changes in environment to be correlated with changes in sediment. A series of samples taken from successive layers of laminae within the same sedimentation unit and at a given sampling point enables changes in the cycles of variation of the assignable causes to be correlated with changes in the sediment. Both of these constitute environmental sampling for which the sedimentation-unit concept is intended.

LOGICAL STEPS FOR THE FIELD DETERMINATION OF SEDIMENTATION UNITS

1. *Define the material to be sampled in terms of the agency or agencies of transportation and the causes of deposition.*—Note that if two agencies of deposition act alternately and portions of the deposits formed by each are left unchanged, the alternate layers cannot be one sedimentation unit

2. *List the environmental factors which determine the statistical properties of a single lamina and of layers of laminae.*—At Cronise Lake examples of the environmental factors are the composition of the sand brought to the playa, the availability and amount of sand supply, the moisture content of the sand, and the magnitude and direction of wind velocity. Examples of the statistical properties are average particle diameter, dispersion of particles about their average diameter, mineralogical composition, and porosity.

3. *Determine which of these factors can be segregated into assignable causes of variation.*—Of the factors influencing particle diameter, the

composition and availability of the source material and the moisture conditions constitute definitely assignable causes of variation. The effects of changes in each of these factors can be predicted. These factors undergo relatively slow variations and for many studies may be considered constant. Wind-velocity variations, as previously shown, constitute a group with both assignable and nonassignable causes of variation. It is necessary to select individually the assignable causes of variation from this group.

4. *Determine whether the remaining factors are nonassignable causes of variation.*—In this way, unsuspected assignable causes may be disclosed. Usually there are factors which cannot be classed definitely as assignable or nonassignable causes. Summer thunderstorms are an example; their occurrence at a specific locality may seem definitely fortuitous. However, their effects on the growth of a dune are predictable; accordingly, they are assignable causes. Local whirlwinds originating on the playa may rarely come close enough to the dune to cause a violent abnormal wind of short duration The occurrence of this event could scarcely be told from the sediment except immediately thereafter. Such an event is thus considered a nonassignable cause of variation.

5. *Trace the influence of each assignable cause on the physical properties of the laminae by considering what happens when the assignable cause undergoes its expected range or cycle of variation.*—This is done by ordinary inductive reasoning guided by local field conditions. The purpose is to seek those conditions which introduce truncated bedding or rapid changes in the laminae; these mark the boundaries of sedimentation units. As long as the only change in successive layers of laminae is a gradual one, the laminae are part of the same sedimentation unit.

Sedimentation-unit boundaries are determined by relatively sudden changes in an assignable cause or by the entrance or exit of another assignable cause. It needs to be established that the change in environment is capable of producing a recognizable change in the laminae. The magnitude of the effect must be great enough not to be marked by the effect of slight fluctuations in the nonassignable causes from one layer of laminae to the next.[8]

[8] The kind of reasoning involved is illustrated by the following oversimplified analysis of the effects of a high-pressure area in the Nevada-Utah region. Southwester-

6. *As a check on the inductive reasoning, re-examine the bedding planes and stratification for discontinuities and rapid changes not indicated by the inductive analysis.*—If these cannot reasonably be attributed to the nonassignable causes, look for some distinguishing characteristic which may afford a clue to an unsuspected assignable cause.

FIELD TECHNIQUE FOR ENVIRONMENTAL SAMPLING

Environmental pattern studies are made preferably where sedimentation is actively taking place so that the assignable causes of variation can be determined with assurance. When some member of a geological formation long since deposited is chosen for study, the environment of deposition must be inferred from the physical and paleontological evidence and by detailed comparison with localities where the same sediment is now being deposited. The postulation of causes of variation and the detection of assignable causes are less certain since the reasoning rests on premises which are inferential and consequently subject to greater error than premises based on observation. This disadvantage is often offset by greater accessibili-

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ly regional winds of increasing intensity will blow out from the high-pressure area during its formation. At the Cronise Lake dune these winds will be deflected westward by the hill on the south. Since increasing wind velocity is favorable to dune growth, a layer of sand will be added to the dune. The average particle size will become increasingly coarser because (1) the material brought to the dune is continually getting coarser and (2) because the transporting power of the wind up the dune slopes and over the top of the hill is increasing.

Continued high winds may remove most of the loose sand on the playa. Sand will continue to blow over the top of the hill, resulting in a net loss of material from the upper part of the dune. On the lower slopes of the dune this condition may be marked by deposition of a layer of coarse sand. The start of erosion marks the upper time boundary of the basal sedimentation unit. During the period of decreasing intensity, little change will occur unless the wind direction shifts enough to obtain a new sand supply. A new sand supply will cause coarse grains to be buried beneath finer sand. Renewal of active deposition marks the base of a third sedimentation unit. Where the layer of coarse grains is missing, truncated bedding will mark the base.

Any complete environmental study will consider the areas of nondeposition and erosion. A complete quantitative environmental study of this dune during such a weather cycle as here postulated requires sets of samples from each of three sedimentation units. From the aerodynamic point of view, each set is best collected as soon as deposition has ceased. From the geological point of view, samples collected after the storm has ceased are preferable because they will yield data comparable to those which may be obtained in the geological record.

ty. Thus a recently uplifted portion of sea bottom which still has the shoreline features well preserved may be preferable for some environmental studies because of easy access.

The choice of a locality for an environmental study of a sediment in process of deposition is best made after a reconnaissance examination has eliminated those localities with poorly developed physiographic forms and those areas of deposition complicated by atypical sources of material or by many local sources of material.

An efficient inductive analysis to determine the sedimentation units should be preceded by a careful field examination of the stratification and bedding and an inquiry into climatic and weather conditions which may constitute assignable causes of variation. With these data at hand, little time will be lost investigating the effects of conditions which are known not to have existed during the deposition of the layers involved in the study.

After the sedimentation units have been determined, one or more are chosen for sampling. Only samples coming from the same sedimentation unit are comparable. Thus it is important to establish the continuity of each unit being sampled, since erosion may have completely removed one or more units in places. The correct picture of the environmental pattern will take into account areas of nondeposition or erosion as well as areas of deposition. A sedimentation unit in the process of formation is especially well adapted for study because its continuity is certain. When the area involved in the study is small, shallow trenches are useful to establish continuity. For large areas where samples are taken hundreds of feet or several miles apart, the continuity can often be established by shallow core samples by ordinary geological methods if the units are quite thick. If the environment has remained fairly constant during the deposition of a considerable thickness of material, samples may be taken from comparable portions of the unit. Ordinarily a channel sample extending the full thickness of the sedimentation unit and perpendicular to the base is preferable. If the purpose of the study is to evaluate the effect of a trend in an assignable cause, samples are taken from consecutive layers of laminae within the sedimentation unit; as shown previously, layers of laminae eliminate effects of nonassignable causes.

To obtain the samples the author has found the following equipment satisfactory: a $1\frac{1}{2}$- and a 3-inch diameter cylindrical, galvanized iron tube closed at one end except for a small opening, a 2-ounce round tin box, a 6-ounce round tin box, a rectangular tube 4 inches by 1 inch for sampling layers in a vertical bank, and a 2-inch by $1\frac{1}{2}$-inch scoop shaped like a dustpan.

CORRELATION SAMPLING

Sampling for correlation by paleontological methods is beyond the scope of this paper. Studies in progress suggest that an empirical adaptation of the sedimentation-unit concept may improve correlation by lithologic methods. Samples from sedimentation units, though desirable, ordinarily cannot be selected, because the determination of sedimentation-unit boundaries presupposes a degree of knowledge which does not exist when correlation of strata is sought.

SUMMARY

Four kinds of sampling classified according to purpose have been described: engineering sampling, descriptive sampling, environmental sampling, and correlation sampling. The essential features of a systematic sampling program for a sedimentary deposit have been considered for the first three kinds of sampling.

For some environmental studies composite samples are desirable; more often samples from individual layers are preferable. The concept of the sedimentation unit enables the field worker to decide rationally what laminae or layers should be included in the sample. The determination of the sedimentation units requires recognition of two types of causes of variation in sediments: those which determine the distinguishing characteristics of individual laminae and those which determine the statistical properties of layers of laminae. Six logical steps for determination of sedimentation units were presented, followed by suggestions on field technique.

ACKNOWLEDGMENTS.—The writer wishes to acknowledge the helpful advice and friendly criticism of Dr. W. C. Krumbein of the Department of Geology of the University of Chicago in connection with the definition of the sedimentation unit and application of the concepts to general cases. Valuable criticisms were contributed by Vito A. Vanoni and Dr. Gordon Rittenhouse of the Soil Conservation Service.

THE MORRISON OF OKLAHOMA AND ITS DINOSAURS

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ABSTRACT

The discovery of Morrison dinosaur bones in Cimarron County, Oklahoma, led to a study of the geology of the area. This investigation brought to light six deposits containing remains of these animals, of which four genera have been identified. The study showed that the Morrison extends down the Cimarron River, beyond Highway 38, north of Boise City. At Robbers' Roost, 4 miles east of the New Mexico state line, the Morrison is unusually thick but thins rapidly toward the east, owing to erosion of a post-Morrison dome. For this reason, and because the Morrison has only a few feet of sediment between it and the Triassic, and because it is overlain by Lower Cretaceous sediments, it seems best assigned to the Jurassic.

INTRODUCTION

In 1931 Morrison dinosaur bones were discovered in the northwest corner of Cimarron County, Oklahoma. The find was made by a crew of road workers on Highway 64, about 100 yards east of the bridge crossing South Carrizo Creek, 10 miles east of the New Mexico–Oklahoma state line. This discovery was reported by the writer in 1932.[1] Since that time five additional deposits of dinosaur bones have been discovered in the general region. Extensive quarry operations have been carried on at the site of the first discovery; and more than 3,500 individual bones, most of them from a single genus, *Brontosaurus*, have been collected. Three other genera, *Ceratosaurus*, *Camptosaurus*, and *Stegosaurus*, have been identified from the area. This work has been financed in part by the Works Progress Administration and in part by the state of Oklahoma.

The finding of the Morrison dinosaur bones in Cimarron County, considerably east of any previously known occurrence, led to a detailed study of the area. As a result considerable light has been thrown on the character of the Morrison formation.

Although the dinosaur bones just mentioned were the first Mor-

[1] J. Willis Stovall, "Jurassic in Oklahoma," *Science*, N.S., Vol. LXXVI (1932), pp. 122–23.

rison fossils to be found in Oklahoma, Lee[2] suspected the presence of the Morrison along the Cimarron in Oklahoma as early as 1901, when he discovered that formation on the Purgatoire River in southeastern Colorado. The next year further field work confirmed his belief and also showed the Morrison to be present on the Canadian River of New Mexico.[3] Since that time many geologists have recognized the formation in the region, and in 1921–22 Rothrock[4] reported several isolated patches of Morrison on the Cimarron River in Oklahoma and on the North Carrizo and Gallinas creeks. The map which accompanies Rothrock's report shows the Morrison cropping out at the following places: (1) at the west edge of Kenton; (2) at a prominent butte 1½ miles north of Kenton; (3) in a small patch where Sections 4, 5, 8, 9, of T. 5 N., R. 2 E., join; (4) in a long narrow strip a short distance west of the Gallinas; and, (5) in a long winding exposure north of Black Mesa on North Carrizo Creek. Recent work has shown this last exposure to be the top part of the Triassic (Dockum formation). The discovery of this and other errors led De Ford,[5] in 1927, to suggest the advisability of a detailed study of the region. Since 1931 the writer has given considerable attention to the area, and in the summers of 1936–37 prepared a detailed geologic map of the Cimarron River valley from the New Mexico–Oklahoma state line eastward to the place where that river leaves Oklahoma. The map (Fig. 1) reproduced in this paper includes only that portion of the Cimarron River valley in Oklahoma in which the Morrison is exposed.

GENERAL STRATIGRAPHY

Since a detailed report, now in preparation by the writer, on the geology of the Cimarron River valley in Oklahoma will soon be ready for publication, only a very brief account of the general stratigraphy of the area is given at this time.

[2] W. T. Lee, "The Morrison Shales of Southeastern Colorado," *Jour. Geol.*, Vol. IX (1901), pp. 343–52.

[3] "The Morrison Shales of Southern Colorado," *ibid.*, Vol. X (1902), pp. 36–58.

[4] E. P. Rothrock, "Geology of Cimarron County, Oklahoma," *Okla. Geol. Surv. Bull. 34* (1925).

[5] Ronald K. De Ford, "Areal Geology of Cimarron County, Oklahoma," *A.A.P.G. Bull.*, Vol. XI (1927), Part II, pp. 753–55.

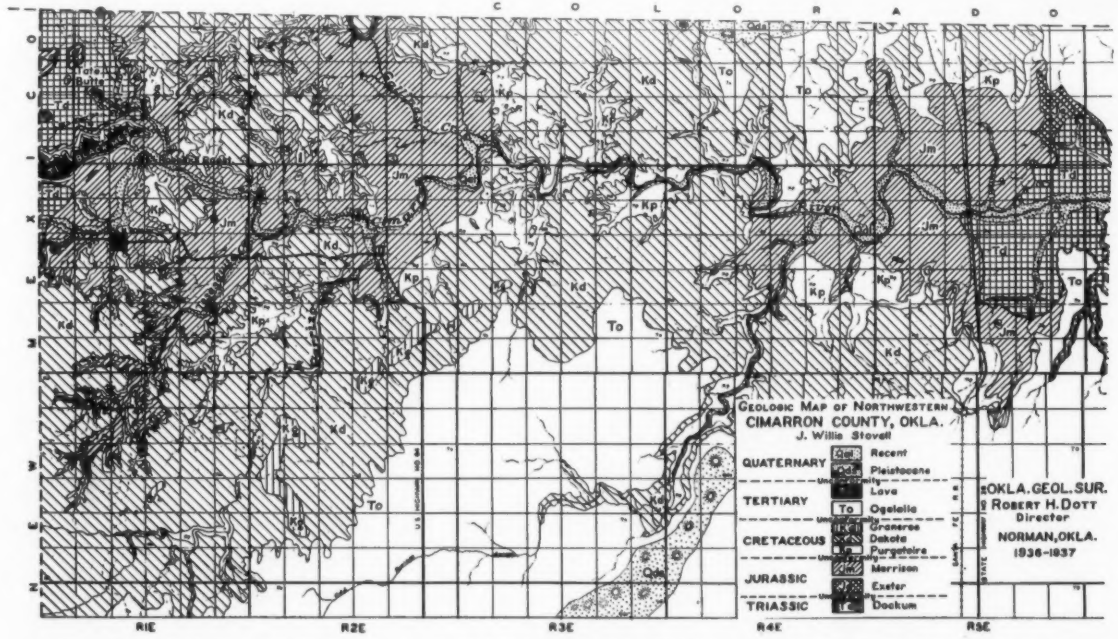

FIG. 1.—Geological map of the northwest corner of Cimarron County, Oklahoma. The outline of the Cimarron River canyon corresponds to the Purgatoire exposures. On this map it appears as a white line with a few small expansions where the Purgatoire covers gentle slopes. Dinosaur locations are indicated with numbers from 1 to 6.

TABLE 1

GEOLOGIC SECTION OF THE CIMARRON RIVER VALLEY

Formation				Description	Feet
CENOZOIC	Quaternary	Recent		Wind-blown sand and stream deposits	2–15
		Pleist.	Panhandle	Wind-blown sand	1–40
			Girty	Stream deposits	1–20
		Unconformity			
	Tertiary	U. Plio.	Basalt	Black to grayish green	66
			Ogalalla	Sand, gravel, mortar beds	5–50
		Unconformity			
MESOZOIC	Cretaceous	Graneros		Sandstone, shale, limestone	135
		Dakota		Massive, buff, cross-bedded, conglomeratic sandstone	185
		Disconformity			
		Purgatoire		Massive, buff sandstone capped with black to gray fossiliferous shale	99
		Unconformity			
	Jurassic	Morrison		Variously colored sandstone, shale, and limestone	465
		Exeter		Massive, white sandstone	18
		Unconformity			
	Triassic	Dockum		Variegated sandstone, shale	66
Minimum thickness					1,043

The Dockum formation of the Triassic is the oldest series of rocks exposed in the area. This may be seen to underlie the Exeter (Jurassic) with slight angular unconformity, immediately southeast of Tate Butte. Nine miles west of the Oklahoma–New Mexico state line the angle between the two formations is much greater, being probably 20°. The Dockum consists of gray and maroon sands and clays, agreeing in this respect with the Dockum of Big Spring, Texas, and elsewhere. Sixty-six feet of the formation are exposed at Tate Butte.

The Exeter is dominantly a white, massive sandstone about 18 feet thick. It is well exposed at Tate Butte and at the New Mexico–Oklahoma state line on Highway 64. It is also present north of Boise City, Oklahoma, where, however, there are no good exposures.

The Morrison rests conformably on the Exeter and is the most widespread surface formation in the valley of the Cimarron. Lee's[6] description, "uniformly variable," is most applicable, for the formation varies rapidly vertically and horizontally. The total thickness is about 465 feet. At several localities the bedding of the Morrison makes a decided angle with that of the overlying Purgatoire of the Lower Cretaceous.

The Cheyenne, the lowest member of the Purgatoire, is a buff, conglomeratic sandstone. This member contains many fossilized logs and fragments of wood. It forms numerous bluffs along the outer limits of the valley. The maximum measured thickness was 66 feet. The Kiowa, which is the upper part of the Purgatoire, is a gray to black shale with considerable platy sandstone. The shale is highly fossiliferous, containing large numbers of *Gryphaea corrugata* Say. The greatest thickness measured was 49 feet. The top of the Purgatoire is channeled in many places, thus indicating an erosion interval prior to the deposition of the Dakota.

The Dakota is a massive, cross-bedded sandstone. The greatest thickness (185 feet) is found immediately south of the main canyon and west of the old town site of Mineral. There it has a threefold character. The lower 85 feet are a massive, cross-bedded, conglomeratic sandstone, which forms conspicuous bluffs on each side of the canyons. Above this is a 1-foot layer of lignite, followed by 46 feet

[6] *Jour. Geol.*, Vol. IX (1901), p. 36.

of grayish shale and ferruginous sandstone. The next 53 feet closely resemble the lowest 85 feet, being a cross-bedded, conglomeratic sandstone.

The Graneros is conformable on the Dakota and is composed of 135 feet of sandstone, shale, and fossiliferous limestone. It contains plesiosaur bones, shark teeth, and *Inoceramas* fragments. The Graneros is the highest division of the Mesozoic in the area.

The Tertiary is represented by the Ogalalla (Upper Pliocene) sands, gravel, and typical mortar beds. The thickness probably does not exceed 55 feet. The average is about 20 feet.

The only igneous rocks in the area are black lavas of Tertiary age which form a conspicuous mesa, known as Black Mesa, about $2\frac{1}{2}$ miles north of Kenton, Oklahoma.

The Quaternary is represented by Pleistocene and Recent stream and wind-blown sand. These sediments are not very thick and are highly lenticular. In a few places they contain the remains of *Elephas columbi*. The term "Girty" is well established for Pleistocene stream deposits, but no name has previously been applied to the wind-blown and loesslike deposits of the southwest. For convenience such deposits are here termed "Panhandle." This name is appropriate because of the extensive deposits of wind-blown sand in the panhandles of Texas and Oklahoma.

STRUCTURE

The panhandle of Oklahoma has been affected by the same movements which disturbed the Rocky Mountains and the foothills to the east. There were several of these disturbances; but in Oklahoma only minor folds, of various orientation, were produced. The first uplift, for which there is evidence in the area, occurred after the close of the Triassic (see Fig. 2). At Tate Butte, and in a more pronounced way at Battleship Butte, a few miles west of Kenton in New Mexico, the Dockum is overlain with marked angularity by the Exeter. In the Tate Butte–Robbers' Roost locality the dip of the Morrison increases from 4° to 7° to the southeast. The next marked disturbance in this region occurred after the close of Jurassic time, when the Morrison was uplifted with warping and truncation. Another minor uplift led to stream channeling in the Purgatoire. Other

slight disturbances occurred in Pliocene time. The two most pronounced folds are located at the opposite ends of the area studied. The westernmost centers just west of the Oklahoma–New Mexico state line north of Black Mesa. This flexure is a dome which has been involved in two well-marked periods of uplift and in two or three less intense disturbances.

The largest structure of the area lies north of Boise City, Oklahoma, on the Cimarron River. This fold is somewhat dome-shaped, symmetrical, and attains a maximum dip of about 10°. The greater axis is in a north-south direction.

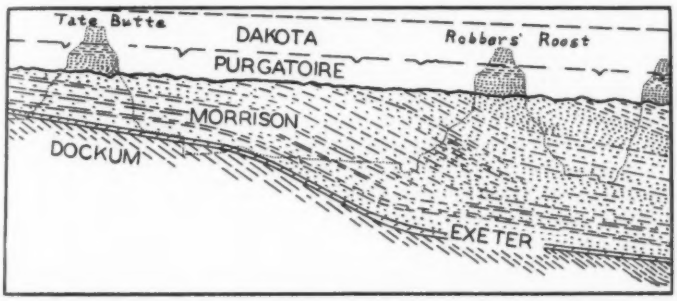

FIG. 2.—Relationship of the Morrison at Tate Butte and Robbers' Roost. Sequence of events in the diagram are: deposition of the Dockum, followed by uplift and planation; subsidence and deposition of the Exeter and Morrison, after which occurred uplift and partial erosion of those sediments, followed by subsidence and deposition of the Purgatoire and Dakota. The heavy line represents the post-Morrison surface; the dotted line, the present surface.

Other smaller anticlinal folds involving the Morrison are found in many places. Some of the most notable are: (1) on both sides of the Gallinas Creek; (2) east of the Joe Brown Ranch; (3) north of Boise City and to the west of Highway 38. The anticlines east and west of the Gallinas Creek, which occupies a syncline between them, have their axes northwest and southeast. The east and west dips are about equal and do not exceed 7°. The eastern fold extends from the Hallock Ranch into Colorado for a distance of almost a mile. The western fold is slightly broader and longer, extending from the Cimarron River into Colorado for a short distance. The fold east of the Joe Brown Ranch is symmetrical and has a northeast-southwest

strike. The dip is about 7°. The small folds north of Boise City are asymmetrical, probably having resulted from solution of strata slightly below the surface. Some of these small folds are very close together with no agreement in the direction of the strike.

DETAILS OF THE MORRISON FORMATION

The Morrison here, as elsewhere, is composed of variegated sands, shales, and a few limestones. The color, lithology, and chemical composition vary laterally and vertically, as has been pointed out by Lee.[7] The color ranges from purple, red, brown, yellow, buff, and turquoise-green to white.

The upper 90 feet of thin platy sands and shales of the Morrison were deposited under conditions which suggest frequent and sudden changes in the sedimentary processes involved. At Robbers' Roost the top 115 feet of that formation are composed of very fine, cross-bedded, and apparently wind-blown sand. The most striking difference between the top 90 feet of Morrison and that portion of the formation which lies beneath the massive white sandstone is the greater thickness of the individual layers of the latter. Conditions of deposition were consistently variable. As a rule, beds of coarse sand alternate with layers of fine sand and silt. Apparently, the coarse sand was deposited by currents of increased velocity due to flooded conditions of the streams. The layers of finer material were deposited when the streams in flood lost their velocity. A few lenses of dolomite and limestone apparently accumulated in shallow lakes.

As was stated above, the Morrison is the most widespread formation in the canyons of this region. It not only forms the floor of most of the canyons but rises high in their walls. In the western end of the area, on the north and south sides of Black Mesa, it appears as a band adjacent to the younger formations. From Kenton eastward it occupies the valley of the Cimarron River and its tributaries from wall to wall, except where masked by alluvium. The Morrison may be seen from 1 to 7 miles up the tributaries of the Cimarron River, and on the Gallinas Creek into Colorado for a distance of 2 miles.

[7] W. T. Lee, "Correlations of Geologic Formations between East Central Colorado, Central Wyoming, and Southern Montana," *U.S. Geol. Surv. Prof. Paper, 149* (1927), p. 17.

Rothrock reported a maximum thickness of 55 feet for the Morrison in Oklahoma.[8] Unfortunately, the sediments from which this section was measured lie beneath the Exeter. Lee's measurements include the Purgatoire and are excessive to that extent at the location measured by him.[9] Lee did not measure the Morrison at the Tate Butte–Robbers' Roost location. He was not, therefore, familiar with the eastward thickening of the Morrison in that region. For Union County, New Mexico, Darton estimated the total thickness of the Morrison to be 362 feet,[10] but apparently he included the Exeter and a part of the Dockum group in that measurement. He says:

> One sandstone which lies considerably below the middle of the formation has been called the Exeter sandstone by Lee. I am confident that it is the same bed which appears continuously in the southwestern part of Union County and in the eastern part of San Miguel County in the middle of the Morrison formation but here increased somewhat in thickness.[11]

Mook has given very careful study to the Morrison in both western Colorado and in Utah. In those regions his measurements show that formation to be about 1,000 feet thick.[12] While the thickness of the Oklahoma section does not approach that of the section measured by Mook, it is greater than the general average for the formation. There is, however, no complete section of Morrison exposed at any one place in Oklahoma; and, in order to get the total thickness, measurements must be combined from three different locations. At Tate Butte there is a thickness of 156 feet. The green shale, which is the top of the Morrison at that location, is carried by a southeast dip to the bed of North Carrizo Creek at Robbers' Roost, where the formation is 219 feet thick. One and one-half miles east of Robbers' Roost, an additional 90 feet are found. The Oklahoma Morrison, therefore, has a total thickness of 465 feet.

The following sections represent the total thickness of the Morrison in the area and show its variable character. The upper and

[8] Rothrock, *op. cit.*, p. 31.

[9] *Jour. Geol.*, Vol. X (1902), p. 32.

[10] N. H. Darton, "'Red Beds' and Associated Formations in New Mexico," *U.S. Geol. Surv. Bull. 794* (1928), p. 307.

[11] *Ibid.*

[12] C. C. Mook, "A Study of the Morrison Formation," *Annals New York Acad. Sci.*, Vol. XXVII (1916), p. 157.

lower limits of the formation were confirmed in the field by Mr Robert H. Dott, director of the Oklahoma Geological Survey, and by Mr. Arthur Wedel, of the Pure Oil Company of Tulsa, Oklahoma.

The thick sandstone at the top of the Morrison at Robbers' Roost does not appear beyond the Gallinas Creek. From there eastward it is the lower part of the Morrison, beginning in the zone of the alternating buff sandstone and purple shales, which is seen in the

TABLE 2

MORRISON SECTION AT TATE BUTTE

S.W. ¼ Sec. 21, T. 6 N., R. 1 E.

Top Purgatoire-Morrison unconformity	Feet	Inches
Alternating beds of green shale and sand, varying in color from buff to brown, talus covered	54	....
Dove-colored, very dense limestone, occurring in layers about 8 inches thick. Layers separated by zones of green shale. Top grades into sandstone. Surface of limestone irregular. Limestone shows many lenses of chert	40	....
White, massive sandstone	34	....
Thin-bedded sandstone and shale. Becomes more massive toward the south, where thick sandstone is in evidence	20	....
Dove-pink dolomite, containing many small dolomite rhombs	...	8–20
Thin-bedded, buff sandstone, containing numerous, easily eroded, bands	8	....
Total thickness at Tate Butte	156	8–20

escarpments along the Cimarron River and its tributaries. In the eastern part of Ranges 2 and 5 some of the low, rounded hills are capped with the limestones similar to those found just above the bed of the North Carrizo Creek.

As shown in Figure 2, the section of the Morrison measured at Robbers' Roost forms a series of rocks higher in the formation than those at Tate Butte to the northwest, owing to the southeasterly dip, which increases from 4° at Tate Butte to 7° at Robbers' Roost. This dip carries the top member of the Morrison at Tate Butte to the bed of the North Carrizo at Robbers' Roost. At the creek level there is an emerald-green shale which corresponds to the top of the Morrison at Tate Butte and at 101 Hill.

The top member of the Morrison at Robbers' Roost is a 115-foot

layer of white, cross-bedded sandstone, which lies immediately beneath the marked unconformity at the base of the Cheyenne sandstone. One and one-half miles southeast of Robbers' Roost these white sandstones of the Morrison are overlaid conformably by a 90-foot layer of Morrison shale, which in turn is topped unconformably

TABLE 3

MORRISON SECTION AT ROBBERS' ROOST

Sec. 34, T. 6 N., R. 1 E.

Top Purgatoire-Morrison unconformity	Feet	Inches
White, cross-bedded sandstone	115	....
Buff, brown-flecked, conglomeratic sandstone	16	....
Alternating layers of brown, platy sandstone, red-to-purple and gray-to-green shale	39	....
White, brown-flecked, cross-bedded sandstone, containing a 2-foot layer of purple shale 6 feet from the top. Ledge-forming	22	....
Variegated, thin-bedded, alternating layers of white, buff, gray sandstone; purple-to-dove-colored dolomite and limestone; greenish shales, occupying the bed of the North Carrizo Creek	27	....
Total thickness	219	....

TABLE 4

UPPER MORRISON SHALE

Sec. 11, T. 5 N., R. 1 E.

Top Purgatoire-Morrison unconformity	Feet	Inches
Alternating layers of variously colored sandstone and shale. Too badly covered with talus to be measured	90	....
Total thickness	90	....

by the conglomeratic sands of the Cheyenne. Thus, the Cheyenne overlies, successively from west to east, Morrison shales which occur well down in the section at two localities; the thick, white sandstone; and finally the top 90-foot layer of shale, establishing beyond a doubt the unconformable relationship of the Purgatoire to the Morrison.

Some of the sandstone members of the Morrison have been converted into quartzite, which is usually near the top of the formation

and has some value as a marker. In the valley between Black Mesa and Kenton one of these quartzites has been tilted to an angle of 12°. Where there is quartzite and where the younger rocks have been removed, it forms hills covered with quartzite "float."

When the quartzite was first studied at the thick exposure north of Kenton, the writer supposed the cementation to be the result of metamorphism by heat from the lava of Black Mesa, which may have formerly covered it. A closer study indicated that the zone of siliceous cementation is of varying thickness, usually penetrating along bedding and fracture planes. This evidence indicates that the quartzite has resulted from deposition of silica, as a cementing material, by meteoric waters.

AGE OF THE MORRISON

It is now generally agreed that the Morrison is Jurassic in age, and the evidence presented in the preceding discussion supports this view. Folding and erosion following the Triassic, and again preceding the earliest-known Cretaceous, in addition to the fact that the Morrison may be considered as a stratigraphic unit, indicate the Jurassic age of that formation.

STRATIGRAPHIC POSITION OF THE BONES

The Morrison has few divisions in the Cimarron River basin which can be traced laterally for any great distance. At Quarry No. 1, on Highway 64, 8 miles east of Kenton, where the following section was measured, there is a buff, very dense sandstone which occurs about 7 feet above the dinosaur bones. This sandstone, however, cannot be distinguished from any of six similar ledge-forming sandstones at Robbers' Roost, the lowest of which lies 168 feet below the top of the Morrison remaining at that location and the highest of which is 32 feet above the lowest. The bone horizon, lying somewhere within this series, should have been from 290 to 324 feet below the top of the original Morrison, provided, of course, that that formation does not become appreciably thinner in the intervening distance. A similar brown sandstone is about the same distance above the bones at dinosaur location No. 2, which is about 1 mile north of Quarry No. 1, and at location No. 3, which is about 3 miles northeast. At locations No. 4 and No. 5, 1½ miles west of Kenton,

the bone-producing layer is ashy gray and the bones are silicified. Here, too, because of the lateral variation of the Morrison, the distance below the top of the formation cannot be very closely determined. Location No. 6 is on the Oklahoma-Colorado state line on the Tucker farm north of Kenton. The bone layer is stratigraphically similar to all of the others and, like them, cannot be placed exactly in the section.

TABLE 5

MORRISON SECTION AT QUARRY NO. 1

Eight Miles East of Kenton on Highway 64

	Feet	Inches
Top Purgatoire-Morrison unconformity		
Thin-bedded, buff sand, almost quartzitic in places, separated from underlying clays by an irregular surface	2	....
Cream-colored shale, banded with light purple	1	....
Purple banded shale with lenses of light-colored hard material	2	4
Dense, purple, hard shale, forming a distinct band of irregular upper and lower surface	1	5
Gray shale. Contains many concretions and dinosaur bones	8	6
Alternating layers of purple, gray, and buff shales, from a few inches to 6 feet in thickness. The lowest one is emerald green and shows in the bed of the Carizzo Creek	35	....
Total thickness	50	3

From Robbers' Roost eastward, buff, ledge-forming sandstones, with which the bones are associated, are found in isolated patches as far as the Kohler farm. One seldom finds more than two or three of the ledges exposed at any one place.

So much lateral variation in the thickness and character of the Morrison suggests changing conditions from place to place, although the unbroken condition of the bones indicates that no marked disturbances have affected them. The fact that they are disarticulated and, in the main, undistorted indicates that they were disturbed only by streams of water and possibly by flesh- or carrion-eating animals. The large size of many of the bones would require a stream of considerable force to move them. Their perfect condition, their degree of concentration, and the fact that an occasional two or three bones are normally articulated suggest that they were moved only a few feet at the most.

It is impossible to give a description of all of the bones excavated at Quarry No. 1 at this time. Most of them are still in their matrix and plaster casts. This discussion will, therefore, be confined to the data necessary to establish, tentatively, the presence of the following four genera: *Ceratosaurus*, *Brontosaurus*, *Camptosaurus*, and *Stegosaurus*.

Ceratosaurus? MARSH

The evidence for the presence of *Ceratosaurus* bones in Quarry No. 1 is inadequate for more than a questionable identification. Several teeth similar to the one shown in Figure 3 (5), a fragment of three fused metatarsals, a small cervical vertebra (Fig. 3 [7]), two relatively small hollow dorsal vertebrae, a number of broad-headed, and tapering ribs from 12 to 20 inches in length (Fig. 3 [9]), suggest an animal of the size and character of *Ceratosaurus*.

Brief descriptions of the bones follow:

Teeth.—The teeth are strong and compressed, with good cutting edges. The fragments present average about 5.1 cm. in length.

Metatarsals.—The fragment of metatarsals consists of the proximal ends of the fused second and third metatarsals with a part of the fourth broken away. The birdlike character of these bones is well demonstrated. The fragment is 10.2 × 15.3 cm. See Figure 3 (6).

Cervical vertebra.—This bone is flat on the anterior end and convex on the posterior end. It has strong neural arches, a short dorsal spine, and well-developed zygopophyses. Its total length is 8.9 cm.

Dorsal vertebrae.—These bones are not complete but are well-enough preserved to reveal something of their true character. The sides and the bottom are deeply excavated, suggesting an hourglass, except for the dorsal region, where the centrum is expanded to receive the neural arches. Broken places reveal a large internal cavity. The centrum is depressed along the neural canal. The upper half of the dorsal spine has been restored in Figure 3 (8). The length of the centrum is 12.4 cm.

Ribs.—The ribs are broad headed and taper to the distal end. If it were not for the presence of the bones described above, these ribs alone would be of little diagnostic value, since they might be confused with those of other small theropods. See Figure 3 (9).

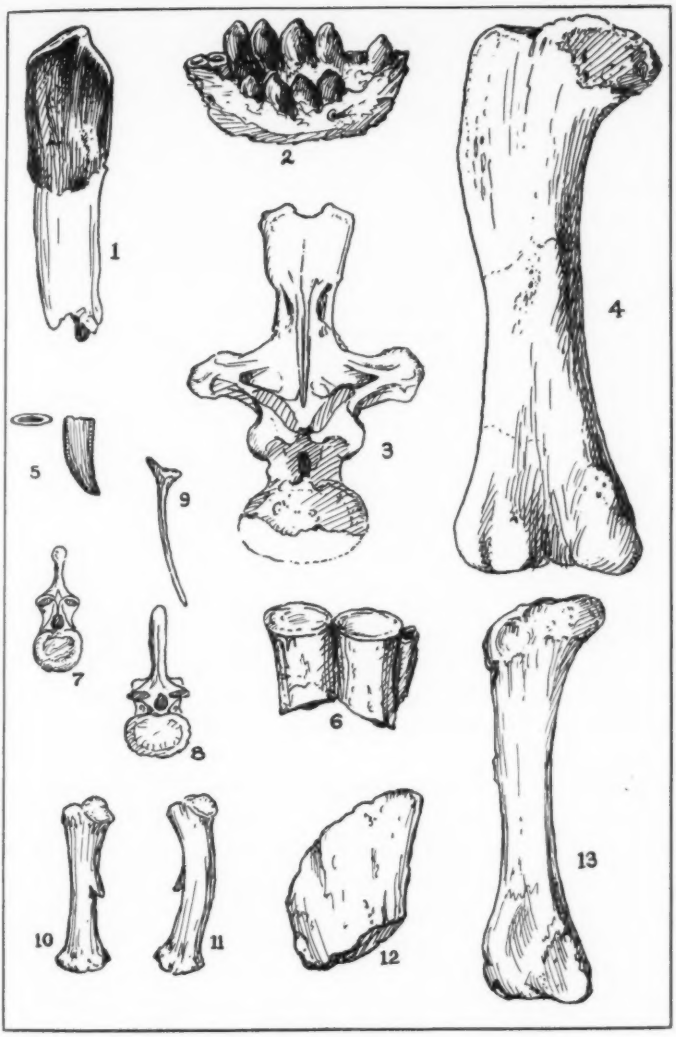

FIG. 3.—(*1*) An individual tooth of *Brontosaurus excelsus* Marsh, length 13 cm. (*2*) A fragment of the right mandible of *B. excelsus* Marsh, length 35 cm., depth 23 cm. (*3*) A dorsal vertebra of *B. excelsus* Marsh, greatest length 130 cm. (*4*) The left femur of *B. excelsus* Marsh, length 178 cm. (*5*) A fragment of tooth of *Ceratosaurus?* Marsh, length 5.1 cm. (*6*) A fragment of the fused metatarsals of *Ceratosaurus?* Marsh, size of fragment 10.2×15.3 cm. (*7*) A small cervical vertebra of *Ceratosaurus?* Marsh, length 8.9 cm. (*8*) A dorsal vertebra of *Ceratosaurus?* Marsh, length 12.4 cm. (*9*) A rib of *Ceratosaurus?* Marsh, length 32.5 cm. (*10*) Front view of the left femur of *Camptosaurus?* Marsh, length 69 cm. (*11*) A side view of the left femur of *Camptosaurus?* Marsh, length 69 cm. (*12*) A dorsal plate of *Stegosaurus* Marsh, greatest length 38 cm. (*13*) A femur of *Stegosaurus* Marsh, length 113.5 cm.

Brontosaurus excelsus MARSH

A large number of *Brontosaurus* bones have been removed from Quarry No. 1. These bones are remarkably complete, although a slight movement in the sediments has fractured them in a few places.

Teeth.—The teeth identified as those of *Brontosaurus* are characteristically spoonlike. The enamel-covered portion has many longitudinal ridges, and in this respect it closely resembles *Morosaurus* as figured by Marsh.[13] The root of the tooth found in the Oklahoma quarry is a little less bulbous than that of *Morosaurus*. The teeth agree closely with those of *Brontosaurus* as figured by Marsh [14] Individual tooth, 13 cm. long. See Figure 3, (1) and (2).

Vertebrae.—The vertebrae are massive and have numerous cavities in the centra. The specimen seen in Figure 3 (3) is a dorsal, the centrum of which measures 16 inches in width. Numerous opisthocoelus vertebrae were found. Greatest length, 130 cm.

Scapulae.—Two very large scapulae from Quarry No. 1 have been identified as belonging to *Brontosaurus*. These scapulae differ slightly in length and width, but the discrepancies are so small that the writer presumes that they belong to the same animal. The upper portion of the scapula is long and narrow without lateral expansion. The proximal end closely resembles *Morosaurus*, but the latter has an expansion toward the upper end. The total length of the long scapula is 138 cm.

Femora.—Both femora are present, and one is almost perfect. The bone is solid, and all trochanters are greatly subdued. The head of the femur has no neck, and the condyles are rounded and much wider than the shaft. The complete femur measures 178 cm. in length. See Figure 3 (4).

On the evidence presented above, this specimen has been identified as *Brontosaurus excelsus* Marsh.

Camptosaurus? MARSH

This genus is represented by several bones which are of small diagnostic value. Identification was based upon a single femur.

[13] O. C. Marsh, unnamed series of plates, *Amer. Jour. Sci.*, Vol. XVI (1878), Pl. V, Figs. 1 and 2.

[14] "Dinosaurs of North America," *U.S. Geol. Surv. 16th Ann. Rept.* Part I (1898), Pl. XX.

Femur.—This bone is relatively massive, measuring 69 cm. in length. The smallest diameter of the shaft is 13 cm. It is markedly curved, has a slightly inflected head, and broad articulating surfaces for the tibia and fibula. A third trochanter occurs on the inside slightly below the middle of the shaft. See Figure 3, (10) and (11). The femur of *Laosaurus*, with which this specimen might be confused, is less massive and has the internal trochanter relatively high on the shaft.

Stegosaurus MARSH

The only bone from Quarry No. 1 identified as that of *Stegosaurus* is a dorsal plate. Many metapodials, vertebrae, and phalanges from that quarry have not been identified. The plate came from the outer margin of the quarry, and it is thus probable that more of the animal may be present in the quarry or in the unidentified bones. An almost perfect femur of *Stegosaurus* was found at location No. 3. See Figure 3 (13).

Dorsal Plate.—This plate is about 25 × 35 cm. and is typical of the genus.

Femur.—The femur is slender and straight. The head is well rounded, and there is virtually no neck. The condyles are separated by a very shallow sulcus. This bone shows no third trochanter. Length, 113.5 cm.

SUMMARY

In a detailed study of the Cimarron River Valley of Oklahoma the known exposed area of the Morrison formation has been extended from a few isolated patches in the western end of the area to a total of more than 105 square miles. The formation agrees in its general character with the Morrison formation wherever it is found. The full thickness (465 feet) is much greater than that previously reported for the Morrison in this and neighboring regions. This fact indicates deposition on a rather steep slope or a greater eastward extension of the Morrison than was generally supposed.

While no vertebrates, other than the dinosaur bones, have been found, six scattered deposits of the remains of these animals indicate considerable local abundance. In Quarry No. 1 the bones are numerous, though dissociated. In this respect they are similar to those at

Quarry 9 at Como Bluff, Wyoming. At Como Bluff, however, eleven genera of dinosaurs have been determined, whereas at the Oklahoma quarry only four genera have been identified. Further laboratory work may bring other genera to light.

The field work has revealed a striking unconformity between the Morrison and the overlying Purgatoire. And although the Morrison is conformable on the Exeter, the Exeter is thin and in turn rests on the Dockum with angular relationship. It is thus evident that all the Mesozoic systems are represented in the Oklahoma Panhandle and adjacent parts of New Mexico and Colorado.

ACKNOWLEDGMENTS.—The writer wishes to thank the Oklahoma Geological Survey for its interest in this study, and especially to thank Mr. Robert H. Dott, who has not only made this investigation possible but who has generously given his counsel and suggestions. The writer wishes to express his appreciation of the services of Mr. Charles Byron Bolar and Mr. Don E. Savage, students of the University of Oklahoma, who served as instrument men during the period of mapping. Thanks are due Drs. Everett Claire Olson and Carey Croneis for criticism and helpful advice in the preparation of the manuscript.

GROOVED LAVA

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ABSTRACT

The original crust of the McCartys flow, near McCartys in Valencia County, New Mexico, is, in restricted areas, broken up into blocks which are turned up on end and capsized like cakes of ice in an ice jam. Many of these blocks are deeply grooved and scratched. These grooves were formed when the bottoms of these blocks, still soft and plastic, were thrust across the irregular solid edges of other blocks.

Pressure ridges are common on the McCartys flow. The medial cracks of many pressure ridges contain triangular wedges of lava whose thin edges point upward. The most striking feature about these wedges is their vertically grooved and fluted surfaces. The triangular wedges were formed when plastic lava was pushed up through a progressively widening medial crack. The irregularities of the wall rock at the bottom of the medial cracks, past which the plastic lava was pushed, produced the grooves and flutes.

INTRODUCTION

In a detailed study of the McCartys flow,[1] near McCartys in Valencia County, New Mexico, it was observed that the basaltic lava is in many places grooved. Because the grooving is so well shown and because its origin is so plainly indicated, the author feels that a brief description and analysis of these features is of interest.

He wishes to express his thanks to Karl T. Benedict, Ralph S. Fellows, Robert S. Folsom, and David D. Rose for assistance in the field work and especially to Dr. Kirk Bryan for consultation in the field and for help in the preparation of this paper. Figure 6 is the work of Dr. Erwin J. Raisz.

THE RUPTURED PAHOEHOE CRUST

The McCartys flow, probably of historic age, is a pahoehoe flow nearly 40 miles long. With the exception of its collapse depressions the original crust is more or less intact over the greater part of the flow. However, in restricted areas, forming somewhat less than 5 per cent of the total area, the crust is broken into fragments which are turned up on end and capsized like cakes of ice in an ice jam, as illustrated in Figure 1. Stearns, in describing the Keaiwa flow, notes a similar condition, for he says: "A few hundred feet from the fissure

[1] Robert L. Nichols, "Quarternary Geology of the San José Valley, New Mexico," *Geol. Soc. Amer. Proc.*, *1933*, p. 453 (abst.).

the pahoehoe crust is broken and turned on end like slush ice in an ice jam. Farther seaward it becomes aa, bristling with jagged and formidable points."[2] The McCartys flow has no aa portions, but the areas of broken crust vary in size from tens of feet in diameter up to several hundred feet and are found at irregular intervals over the entire 40 miles of the flow. The depth to which the crust is broken could not be measured, but it seems likely that the ruptures are only

FIG. 1.—An area on the McCartys flow, Valencia County, New Mexico, showing the blocks and fragments of the broken pahoehoe crust.

superficial and that below 3 or 4 feet the basalt of the flow is compact.

The average thickness of these upturned fragments indicates that the breakup must have occurred when the crust was about 1 foot thick. These fragments were not engulfed in liquid lava, and there is no evidence that any liquid lava was intruded among them, although this result would be expected. This apparent lack of engulfed fragments is perhaps due to the fact that the bottom fragments,

[2] Harold T. Stearns, "The Keaiwa or 1823 Lava Flow from Kilauea Volcano, Hawaii," *Jour. Geol.*, Vol. XXXIV (1926), p. 342.

which would be the ones engulfed, are buried so deeply as to be invisible. Lacroix,[3] in his work on the lavas of Réunion, has described similar ruptured pahoehoe surfaces whose fragments were in places engulfed and surrounded by secondary lava.

As these features have not been observed in the process of formation and as their distribution offers no clue as to their origin, we must, in a discussion of their formation, fall back on a general analysis of the conditions present during the movement of a basaltic lava flow.

After a flow has been running past a point for some time, the liquid lava is not in contact with either the atmosphere or the ground but flows within a carapace of almost solid lava, which, as it cools, develops shrinkage cracks. If, after a carapace has been formed, the quantity of flowing lava is increased, the crust will be elevated, and during the elevation may be broken on the pre-existing shrinkage cracks. This fragmented crust might thereafter be further broken and the blocks rotated and differentially moved by the viscous drag of the molten lava. Daly[4] has suggested that the viscous drag tends to break the crust in areas where strong irregularities of the underlying surface exist.

These areas have significance with regard to the thermal history of the lava, for during their formation liquid lava would be exposed to the air. Their existence, therefore, involves an unusual loss of heat; and, other things being equal, one would expect a lava flow characterized by such areas to be shorter than a flow without such areas. Their scarcity on the McCartys flow is compatible with its relatively great length of 40 miles.

GROOVED LAVA

The fragments of the broken areas just described are angular, irregular, and highly vesicular. The bottoms of many of these blocks show deep grooves and scratches, which remind one of glacial striations or slickensides except that they are deeper and better defined

[3] Alfred Lacroix, *Le Volcan actif de l'Ile de la Réunion et ses produits* (Paris: Gauthier-Villars, editeur, Libraire du Bureau des Longitudes, de l'Ecole Polytechnique, 1936), p. 96.

[4] R. A. Daly, "The Geology of Ascension Island," *Proc. Amer. Acad. Arts and Sci.*, Vol. LX, No. 1 (1925), p. 17.

and the rock is not polished (see Fig. 2). The grooves vary from mere scratches up to marks an inch deep. Some are straight, and some are slightly curved. They almost always occur on that side of the block which has the smaller and fewer vesicles and which was evidently the bottom of the crust.

They must have been formed when the lower sides of the blocks were still soft and plastic, as such grooves could not be made in solid and brittle lava. Moreover, small knobs of lava were plowed out of deeper grooves, a process impossible if the lava were not plastic. If the lava had been too fluid, the grooves might have formed but would have been filled in by flow. As shown in Figure 2, many grooves are straight and the grooved areas are relatively flat, as if a small thickness of the original block had been planed off. That the grooves may be curved and that they may vary in depth from place to place on the same block is well shown by Figure 3. The roughness of the grooved surface is shown by Figure 4. This roughness indicates that in places partial crystallization had already taken place when the grooves were formed. The grooves are similar to those on the surface of bricks having a coarse grout, or to grooves made in slush ice by a shovel or other instrument. The roughness and abrupt discontinuity of the grooved areas distinguish them from slickensides, glacial striations, and other grooves.

The mechanism by which the grooves were formed is illustrated in the three diagrammatic sketches of Figure 5. A section of the crust (*A* in Fig. 5) is divided by a crack into blocks *x* and *y*. The top of the crust, which is cold, is therefore brittle and hard, while the bottom, still hot, is soft and plastic. *B* shows the crust buckled up after it had been subjected to compressional forces, while *C* shows block *x* overthrust on block *y*. Grooves are formed on the underside of block *x* as this soft surface is pushed across the upper rough hard edge of block *y*. If the overthrust block is pushed straight across the underthrust block, the grooves are straight; if it is pushed with a rotating motion, the grooves will be curved.

In a few places blocks were found which were grooved on the top of the crust rather than the bottom. If thin flow-units[5] covered por-

[5] Robert L. Nichols, "Flow-Units in Basalt," *Jour. Geol.*, Vol. XLIV (1936), pp. 617–30. See also J. E. Richey, "Tertiary and Post-Tertiary Geology of Mull," *Mem. Geol. Surv., Scotland, 1924*, p. 114.

FIG. 2.—Grooves and scratches on an upturned block of lava

FIG. 3.—Curved grooves on basalt

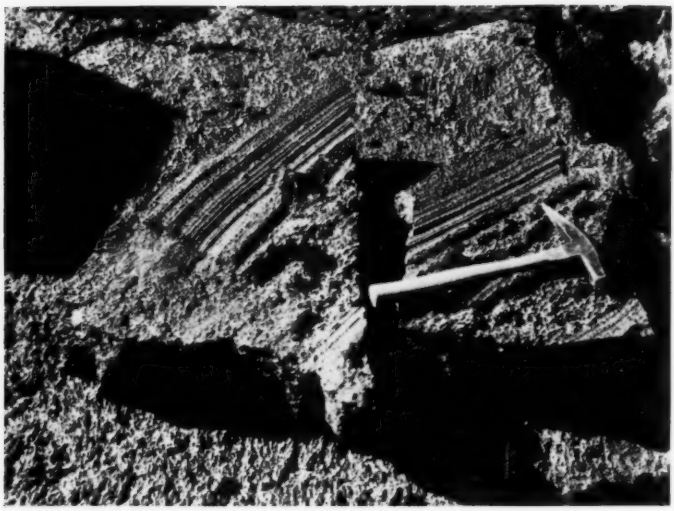

FIG. 4.—Illustrates the rough, grooved surface on the bottom side of a fragment about 6 inches thick.

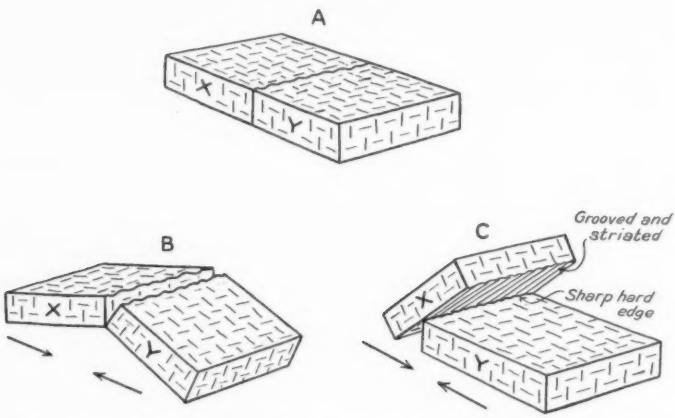

FIG. 5.—Diagrammatic sketches illustrating the formation of the grooves. Arrows indicate direction of compressional forces.

tions of the flow and if they were overridden by a block a short time after being extruded, their soft tops might be grooved. That the McCartys flow contains such thin flow-units is well shown on the walls of some of its larger cracks, where flow-units from a few inches to a few feet in thickness may be seen.

Somewhat similar grooves on lava are described by Stearns:

> In several places the flow was confined to channels, and it happened that a row of old driblet cones stood at right angles to the direction of one of the main channels. As a result these cones, called Lava Plastered Cones, formed a dam to the flowing lava, thereby causing it to pond. . . . . The dam held long enough for the ponded lava to crust over, but the lava soon found an outlet and drained seaward. . . . . The pond of lava must have drained rapidly, because the shore lines are preserved only at high levels. In places blocks of crust from the upper shore line slid down on the sides of the Lava Plastered Cones to the present level of the flow while the lava was still viscous, as is indicated by the "shark teeth" slickensides developed on the sides of the cones by the sliding crusts.[6]

Daly[7] has also described grooved and striated lava produced by the sliding of the crust of a flow on its underlying weaker and softer portion. These grooves were formed at the top of the soft subcrustal material.

The grooved lava described by Hodge is similar to that described in this paper. In describing it, Hodge writes:

> These blocks were formed by the upper portion of the flow freezing to a depth of ten to fifteen feet. The lava beneath, kept viscous by the heat-nonconducting overcoat, moved down the slope and fractured the upper solidified crust just as ice is ruptured on the surface of a stream. Unlike ice blocks on the surface of a winter stream, however, these blocks of lava did not float gently down, but were rolled over and over and in some places squeezed and hoisted up into jagged piles. Some of these massive blocks were not frozen rigid, but retained enough plasticity so that as they were jostled along they gouged each other and left in their sides enormous grooves.[8]

Collapse depressions are common on the McCartys flow. They vary greatly in size and shape. Most of them are a few hundred feet long, 50–100 feet wide, and as much as 20 feet deep. Figure 6 is a sketch of a cavelike collapse depression in the McCarty's flow. The vertical opening into the cave is about 5 feet in diameter and the

[6] *Op. cit.*, pp. 342–43. [7] *Op. cit.*, pp. 20–21.

[8] Edwin T. Hodge, *Mount Multnomah* (Eugene, Ore.: University of Oregon, 1925), p. 58.

surface of the flow is 10 feet above the present floor of the cave. The cave is floored with mud and silt, covering, undoubtedly, blocks of lava which fell from the collapsed part of the roof. The lower $2\frac{1}{2}$ feet of the opening of the cave is grooved and striated for about four-fifths of its circumference. At the time of the collapse, the upper part

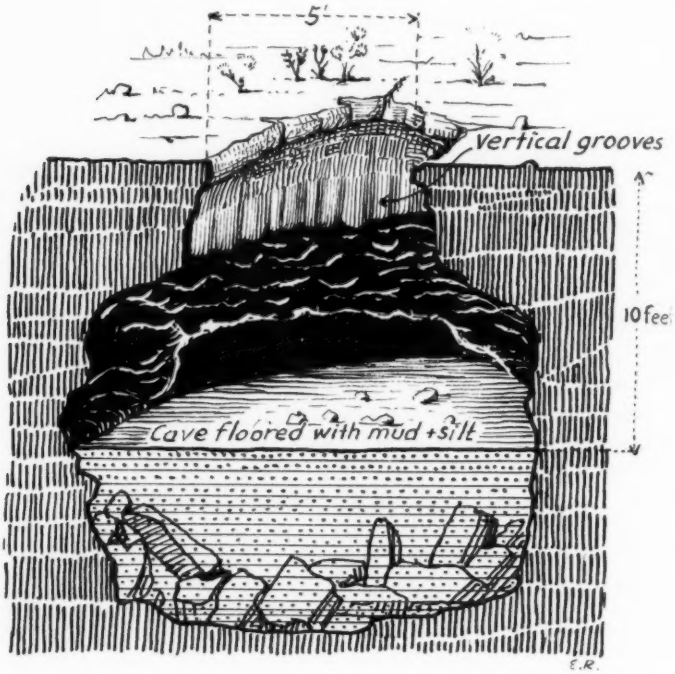

FIG. 6.—Vertical grooves on the walls of a cavelike collapse depression

of the crust was hard, while the lower part was still soft and plastic. When the upper, solid part of the crust, in falling, scraped across the lower plastic part, these grooves and striations were produced.

Jaggar has described somewhat similar grooved markings, formed in lava inside Halemaumau pit, in the following words: "When the entire lava column of this bench material has lowered rapidly, it has fractured into terraces on the insloping funnel wall of old rock, and

the terrace faces show scraping made by the sinking block of the next terrace below."[9]

GROOVED AND FLUTED SQUEEZE-UPS

Pressure ridges are characteristic of almost the entire length of the McCartys flow. They vary greatly in size, and many are as much as 25 feet high and 500 feet long. The sides of the pressure ridges are steep, tentlike; and almost without exception a medial crack runs parallel to the crest. This medial crack varies in width from a few feet to as much as 15 feet.

The medial cracks of many pressure ridges, found on the last mile of the McCartys flow, contain triangular wedges of lava whose thin edges point upward. Such a wedge is well shown by Figure 7. The most striking feature of these wedges is that most of them have vertical grooves and flutes, which are well shown in Figures 8 and 9. These smooth grooves and flutes stand in decided contrast to the rough irregular wall rock of the medial cracks. In a few cases the wall rock near the bottom of the medial cracks is also grooved and fluted, the grooves and flutes on the wall rock matching similar grooves and flutes on the triangular wedges. In size these grooved wedges vary greatly. The largest are 30 feet long, 10 feet high, 4 feet thick at their bottom, while the top is usually about an inch wide. No triangular wedge was found whose apex reached to the top of the medial crack. The tops of many of these grooved wedges are composed of highly vesicular frothy lava that changes within a few inches into a more massive variety. This is well shown in Figure 10.

These wedges were formed after the formation of the pressure ridges, as is shown, first, by the fact that they are not so jointed and cracked as the pressure ridges, and second, by the fact that these grooved wedges are larger than any cracks on the flow with the exception of the medial cracks of the pressure ridges. That these grooved wedges are best considered as "squeeze-ups" seems evident. They are apparently formed in the same way as was the fluted spine of Mont Pelé, which was forced, as a viscous mass of lava, through

[9] T. A. Jaggar, "Lava Stalactites, Stalagmites, Toes and 'Squeeze-Ups,'" *Volcano Letter*, No. 345 (Aug. 6, 1931), p. 1.

FIG. 7.—A triangular wedge of lava found in the medial crack of a pressure ridge

FIG. 8.—A grooved and fluted wedge in the medial crack of a pressure ridge, bent over by gravity when in the plastic condition.

a more or less circular orifice whose irregular walls grooved and slickensided it. Hovey, in writing of the spine of Mont Pelé, says: "The northeast side of the spine presents a fairly smooth, vertically grooved surface, as if it had been slickensided by friction against the side of the conduit during its ascent."[10]

While the pressure ridges were being formed, no open cracks continuous with the subcrustal liquid lava could exist because of the

FIG. 9.—A grooved and fluted wedge slightly arched over by gravity

compressional forces active during their formation. However, after the pressure ridges were formed, a period of relaxation undoubtedly occurred, during which the medial cracks were opened at the bottom. By this time, however, the subcrustal lava was so viscous that, instead of running out of the medial cracks as a mobile liquid, it was pushed up through them as a highly viscous mass. The irregularities at the bottom of the medial cracks produced the grooves and flutes; and, as the lava was pushed up, the crack progressively

[10] E. O. Hovey, "New Cone of Mont Pelé," *Amer. Jour. Sci.*, Vol. XVI (1903), p. 278. See also Howel Williams, "Geology of the Lassen Volcanic National Park, California," *Univ. Calif. Publ. in Geol.*, Vol. XXI, No. 8 (1932), p. 319.

widened, giving a wedge-shaped form to the squeeze-up. Some of these narrower wedges were so plastic that, after they were pushed up, they bent over, as is shown by Figures 8 and 9.

In one case the grooves and flutes ran across the wedge in an oblique direction, instead of running vertically, as is usually the

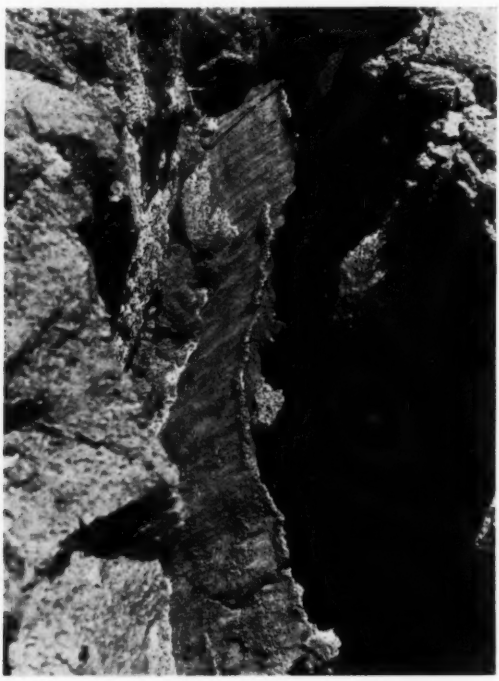

FIG. 10.—Shows the frothy lava at the apex of a grooved wedge

case; apparently this was the result of a horizontal movement between the two sides of the pressure ridge as the plastic lava was being squeezed up. That the medial cracks of the pressure ridges did not all extend down to the subcrustal lava is indicated by the fact that the wedges are not found in all of the medial cracks and that they occupy only a small portion of those in which they are found. That the wall rock near the bottom of at least a few of the medial

cracks was soft and plastic when the wedges were formed is shown by the fact that it also is grooved and fluted, apparently by the friction of the wedges as they moved past the wall rock.

OTHER EXAMPLES OF GROOVED LAVA

Features similar to these grooved squeeze-ups have been described by Colton and Park from one of the flows of the San Francisco volcanic field of Arizona. They write, in describing these squeeze-ups:

> Through this fissure basalt in a plastic condition has been squeezed. The sides of this basalt tongue are grooved, conforming to the walls of the fissure, and slickenside surfaces are usually present. . . . . Again, the thin plates of basalt by the effect of gravity have arched over as they were pressed up into the air. . . . . All these facts testify to the plastic nature of the basalt.[11]

Jaggar has also found these grooved squeeze-ups inside Halemaumau pit. He writes:

> In the history of "bench magma" inside Halemaumau pit there have been many occasions when the crags of semi-solidified basaltic paste at 900° C., forming the walls of the container of the lava lakes—not the walls of the pit—have risen as separate pencils of paste within other material of greater hardness. When they did this, they showed scraped surfaces.[12]

The so-called "barnacle stalactites" described by Jaggar,[13] formed when plastic lava has been squeezed through small cracks in cavern walls, are also grooved.

Another interesting example of grooved lava has been described by Bartrum.[14] A dike which had invaded scoriae and lapilli was found on whose sides was developed a perfect series of slickenside-like grooves and striations. Bartrum concluded that the striations were formed when the dike material was soft. It is also obvious that the process must have occurred very near the surface, where the dike magma was viscous enough to retain grooves and striations. At depth the dike magma would be fluid and would therefore form a

[11] H. S. Colton and Charles F. Park, Jr., "Anosma or 'Squeeze-Ups,'" *Science*, Vol. LXXII (1930), p. 579. See also H. S. Colton, "Quetschformen des Basalts," *Natur u. Volk*, Band LXIV, Heft 5 (1934), pp. 182–88.

[12] *Loc. cit.* [13] *Ibid.*, p. 3.

[14] J. A. Bartrum, "Lava Slickensides at Auckland," *New Zealand Jour. Sci. and Tech.*, Vol. X, No. 1 (1928), pp. 23–25.

close contact with the wall rock, preventing the formation of grooves and striations. A study of dikes found intruding the agglomerates and breccias of composite cones might yield additional examples of this phenomenon.

Brigham, in describing an example of grooved lava from the Hawaiian Islands, writes:

> The inside of the blow-hole was of a brown color, smooth as if turned, and grooved horizontally. No vertical striae could be distinguished, but as these horizontal grooves seem to correspond to the strata of the adjoining crater walls, I suppose that the projecting ridges mark the more solid substance of these strata which would be in their centre, while the scoriae which separate the beds to some extent, would permit the deeper action of the vapors that have formed the hole. The wearing force must have been chemical rather than mechanical, as the wall of the crater adjoining, which is not more than twenty-five or thirty feet thick, would have given way to any violent explosion.[15]

The author of the present paper doubts the chemical origin of these grooves. The suggestion is tentatively advanced that they are similar to the spiral structure in the throats of the so-called "mortars" found in the craters of the Moon National Monument. Stearns has described this structure as follows:

> A few feet from the edge of the fissure there are a dozen little towers of lava from two to five feet high, apparently developed by lava accumulating around jets of steam or gas. The throats of most of those examined exhibited a spiral structure. Similarity of this structure to the rifling of a cannon and similarity in size and shape to the mortars used in the Civil War have led to the term "mortars" for these forms.[16]

No mechanism for the formation of this spiral structure is advanced by Stearns. Nevertheless, it seems evident from his description and photographs that it is formed by the flow of viscous lava in much the same way as is the ropy structure so common on pahoehoe flows.

[15] William T. Brigham, "The Volcanoes of Kilauea and Mauna Loa," *Mem. Bernice Pauahi Bishop Museum*, Vol. II, No. 4 (1909), pp. 11–12.

[16] Harold T. Stearns, "Craters of the Moon National Monument," *Geog. Rev.*, Vol. XIV (1924), p. 370.

THE CLASSIFICATION AND ORIGIN OF BEACH CUSPS

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ABSTRACT

Among shore features, beach cusps have been the most difficult to explain. This is because of the quickness with which they grow when the exact adjustment required between waves and beach materials occurs.

Beach cusps are here classified and the process of formation of each class described and explained. The fifth class is especially interesting and important as it is the one most commonly observed and the most difficult to explain.

Numerous intercusp spaces were measured. These measurements show that the apparent uniformity of spacing of cusps is deceptive. Uniformity of spacing sometimes holds for short distances, but in a series of any considerable length the intercusp spacing commonly shows a wide variation.

There are few minor shore forms whose explanation has proved so difficult and puzzling as those triangular features of the foreshore known as beach cusps. They will be found at times on any shore that is covered with a considerable amount of loose material and that is subject to wave action. They form whether the material is of mud, sand, or gravel, although they usually develop most perfectly on those beaches where the preponderance of the material is clean sand. Although not all cusps are formed in the same way, they are all a result of the work of the waves and their size and their spacing are determined by the size, character, and direction of the waves. The smaller the waves, the smaller and closer together will be the cusps.

Sometimes the waves beat on the shore for hours while the beach remains hard and smooth. Then, with almost no appreciable change in the wind or waves, cusps may form in great numbers in a short time. They form only under conditions of very delicate adjustment of forces and materials, and it is the rarity of the occurrence, combined with the quickness of action when it does occur, that has caused the explanation of the origin of cusps to be so elusive.

For more than a hundred years beach cusps have been observed and described and various theories of their origin suggested. John-

son[1] has summarized the literature of the subject. He finds none of the proposed explanations acceptable and ends by stating a hypothesis of his own, which is:

> Selective erosion by the swash develops from initial irregular depressions in the beach shallow troughs of approximately uniform breadth, whose ultimate size is proportional to the size of the waves, and determines the relatively uniform spacing of the cusps which develop on the inter-trough elevations.

He describes what he calls the "ideal cusp," and would apparently relate all cuspate beach forms to this ideal although he says: "The actual variations in form are numerous and wide." He, in common with most other investigators, evidently regards all cuspate beach forms as having the same origin. However, Johnson's closing statement, "the author has found no feature of beach cusps which is incompatible with the theory, while the assumed conditions of wave action appear to rest on a reasonable basis," leaves one with the feeling that he does not regard the question as entirely settled.

The material for this paper was obtained through observations on the east shore of Lake Michigan and the numerous near-by inland lakes, which are ideal laboratories for the study of beach forms and processes. Clean sand and gravel beaches are numerous. There is no appreciable tide and the clearness of the water in both the large and small lakes is such that the bottom can be seen easily to a considerable depth.

Nowhere in the literature of the subject has there been any attempt to classify beach cusps, and apparently all writers have regarded them as being all formed in the same way. However, after observing and measuring cusps along the shores of many lakes, large and small, it became evident that not all cuspate beach forms have the same origin and that they can be divided genetically into at least five classes.

1. *Very large capelike cusps formed during storms along beaches that are susceptible to considerable erosion and deposition* (Fig. 1).—Along sandy shores they are destroyed and again re-formed during nearly every heavy storm. They probably form best along a shore where the underwater terrace slopes gently and has on it an excess

[1] D. W. Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, Inc., 1919), pp. 457–86.

of sand. Under such conditions great changes take place rapidly during storms. Quantities of sand may be brought in and piled up on shore to a depth of several feet, where formerly it was only slightly above lake-level. Then, with a storm from another direction, there will be a change in the waves and currents and great quantities of sand will be quickly worked out from shore again. Under such con-

FIG. 1.—Giant cusps are caused by nearly every great storm by irregular deposition and erosion.

ditions beach drifting and sand transportation by shore currents result in the formation of capelike projections cuspate in form. As would be expected, these cusps are considerable distances apart and very uneven in their spacing. A series of them measured south of the entrance to the harbor of White Lake on Lake Michigan were spaced as follows: 216, 96, 414, and 201 feet. Another series formed in the same way and in the same place three weeks later measured 204, 132, 168, 1,050, 186, 126, and 345 feet. To the north of the entrance another series formed at the same time had an intercusp spacing of 315, 174, 660, 156, 426, 234, 297, and 228 feet. These

forms varied somewhat in shape, but for the most part had broad bases and extended out into the lake 25–75 feet.

2. *Large cusps which have their apexes continuing out into the lake as a ridge of sand on the lake bottom* (Fig. 2).—Those lakes that have a plentiful supply of sand on their beaches and an offshore profile above the curve of equilibrium often have sand ridges on their terraces. These ridges are caused by the waves and currents

FIG. 2.—Cusp built as the result of a sand ridge on the subaqueous shelf joining the shore.

and vary in size and spacing according to the supply of sand, the size of the lake, and the strength of the winds. Their exact method of formation is not known. They are possibly related to those submarine ridges often found lying nearly parallel to the shoreline in larger lakes and bays and called "ball and low" by some writers. They are not entirely fixed in position but migrate, especially during heavy storms. Where the ends of the ridges join the shore, as they sometimes do, the increase in the supply of sand at the shoreline results in the formation of cusps.

This type of cusp was observed in considerable numbers on Silver

Lake, which is situated near Little Point Sable on the east shore of Lake Michigan. They have also been mentioned by I. D. Scott[2] as being present on Douglas Lake in Michigan.

Silver Lake lies just east of a large dune area, the lee side of which forms the west shore of the lake, and consequently its shores and bottom are very sandy. On the east and southeast sides of the lake the bench or underwater terrace extends out a long distance and the water is shallow, the average depth 200 yards from shore being not more than 4 or 5 feet. An examination of the old shorelines shows that the water of the lake was formerly several feet higher. The lowering of the water line has in effect produced a shoreline of emergence and caused the underwater terrace to be out of adjustment with the present wave action. The result has been the formation on the lake bottom of sand ridges as described above. In this case they are 10–30 feet wide, 1–2 feet high, and 40–200 feet apart. They are only very roughly parallel to each other. On some parts of the lake they lie almost perpendicular to the shoreline while in other places they make an acute angle with it. Scott[3] describes them as having a radial arrangement on Douglas Lake, and there is a suggestion of this on Silver Lake. Where they join the shore the resulting cusps often reach 40 or 50 feet out into the lake before passing beneath the surface of the water and have a width at the shoreline of 30 or 40 feet. Their spacing, which is determined by the spacing of the ridges, is quite uneven. Measurement of a series of such intercusp spaces on the shore of Silver Lake gave the following figures: 102, 96, 54, 81, 45, 69, 66, 33, 69, 36, 75, 54, 66, 84, and 108 feet.

3. *Cusplike forms that occur individually along the beach as a result of deposition or erosion resulting from the presence of an obstruction.*—For completeness, this class should include also other individual forms no matter what their origin, such as delta cusps.

An obstruction a short distance in front of the shoreline may cause either erosion or deposition depending on the size and shape of the obstruction and the direction and force of the water movement. If the conditions are such that there is a relatively quiet area between the obstruction and the shore, deposition will result and the

[2] "Inland Lakes of Michigan," *Mich. Geol. Survey* (1921), p. 111.

[3] *Loc. cit.*

waves coming in from each side of the obstruction may form this material into a cusplike form. On the other hand, if the waves and currents are moving in such a way as to produce a relatively strong current between the obstruction and the shore, erosion will take place and the eroded sand may be deposited down the shore to leeward at the point where the current slackens, and may here be formed into a cusp. Such cuspate forms, however, are purely individual features and never give rise to a series of cusps, although they may sometimes appear to do so because of the accidental presence of cusps due to other causes. This is probably what has led some observers to think that a cusp series like that of Class 5 might be started by the presence of an obstruction on the beach.

4. *Very small cusps formed at the lower ends of grooves which are sometimes formed just above the water line and are perpendicular to it.*—These grooves are formed by the gentle onshore "slop" of a "dead sea" when it moves on shore perpendicular to the shoreline. They are a result of the water of the retreating wave washing parallel grooves in the sand just above the plunge line. They probably would not form if the sand had a perfectly homogeneous plane surface of uniform hardness, density, and size of grain, and the retreating water everywhere had the same velocity. But such uniform conditions never are present, so the retreating water forms small channels perpendicular to the water line. At the lower end immediately above the water surface the ends of the ridges between the channels are pointed into cusps. Such channeling does not occur if the waves break, nor does it take place if the waves do not come in perpendicular to the shoreline. When for any reason an occasional "slop" comes on shore at an oblique angle, the grooves and cusps are immediately obliterated by the slight beach drifting that results, but they re-form immediately with the next gentle wave whose axis is parallel to the shoreline. For this reason such forms are never very large and never develop into cusps of Class 5. A steep slope of the beach just above the water line seems to be favorable because of the greater velocity of the returning water. The best example of this type of cusp ever observed by the author was just north of the White Lake harbor piers on the shore of Lake Michigan. The "slop" which was about 10 inches high, caused groovings from 1–6 inches

apart and about 12 inches long, with the cusp form at the lower end of the ridges. Whenever a wave came in at an oblique angle these ridges and cusps were wiped out, only to re-form with the next favorable wave. A similar smaller series was observed several times also on the sandy shores of what is sometimes locally known as Fisherman's Cove at the White Lake end of the north pier. Here conditions favorable for their formation sometimes result from the swells from Lake Michigan which come in along the channel.

Cusps of this kind have been described by D. W. Johnson[4] and reproduced by him in the laboratory. He apparently believed them to be similar in kind to those discussed later in this paper under Class 5. However, since cusps of Class 4 will be destroyed immediately by breaking waves, or by the slightest amount of beach-drifting, it is evident that they are never changed over into those of Class 5.

5. *The "ideal cusps" which usually occur in series and come nearest of all to being evenly spaced.*—This is the type most frequently noticed on the beach and the one most difficult to observe in the process of formation. The conditions of adjustment between waves and shore under which these cusps form are very delicate, and there is very little latitude of action in the process. However, when the proper adjustment does occur the formation of the cusps is very rapid, sometimes almost instantaneous. But after the cusps are once formed, a considerable change in wave conditions is required to obliterate them. Consequently, when they are once established the waves may play about them for days, often modifying their shape, but being totally unrelated to the process of their formation. This is likely to be very misleading to the investigator who starts with the finished series of cusps, and who may be led to a deductive explanation because of the great difficulty of making direct observations during their growth.

Observation of newly formed cusps of this class indicates that they are a part of a previously formed ridge of some sort. This is usually a newly formed beach ridge although in some cases it may be the rather sharp edge formed by the recent cliffing of the beach sand by the waves. It is also probable that old, smooth beach ridges

[4] *Op. cit.*, pp. 475–76.

occasionally have beach cusps formed on them when the right wave adjustment occurs. However, in the greater number of cases the cusps are formed in recently built beach ridges which have been broken through by the waves under a very close adjustment of the relation between height and uniformity of wave and that of the height and shape of the ridge on which it is acting.

This process was first observed by the author on the shores of Crystal Lake near Frankfort, Michigan. This lake was a part of Lake Michigan in pre-Nipissing time. Its water is clear and in many places its sandy shores are very similar to those along the east shore of Lake Michigan itself. Thus it is an ideal laboratory for the study of shore processes. At the time of the observation a considerable sea had been running the day before and a new beach ridge had been built but no cusps formed. During the night the wind and sea had gone down, but instead of falling calm, as is so often the case on inland lakes at night, a gentle, steady breeze had continued which caused a very regular series of waves perhaps 2 inches in height to beat on the shore for several hours. By sunrise these had built up a secondary beach ridge at the water's edge about 3 inches high. As the sun rose there was a slight increase in the wind velocity, which held steady for several minutes. As the waves increased a little in size it was noticed that the small beach ridge was being breached at various places simultaneously throughout its length. The next few waves somewhat deepened many of the breaks, and immediately where the openings had formed the up-and-back movement of the swash in which the water describes a parabolic path started in the openings, and in a length of time that could not have much exceeded 100 seconds a perfect system of beach cusps had formed.

It might seem from this description that the cusp-spacing would be very irregular, but it was not. There are two reasons for this. The initial break was apparently caused by a single wave that was larger than those that had built the ridge. Now a wave is not of the same height throughout its length, but varies somewhat, and there is some regularity in this variation. Again the parabolic swirl of the water when it comes into the openings made by the wave tends to give a regular spacing to the indentations and projections. If

two small openings happen to be very close together, they are likely to become one larger opening, while an opening that is slightly too wide will be partly filled with material washed from the adjoining incipient cusps. The completion of the process is dependent on the continuance for a short time of waves of the same size and character as the one which caused the original breaks.

The exactness of the process was made evident at several places along the shore where the cusp series was broken. At one place the direction of the shoreline changed for a few feet. Here something of a beach ridge had been built, but, largely because of the change in direction, it was not in adjustment with the cusp-building processes; consequently the shore was left smooth and clean. At another place in front of the shoreline the water was considerably shallower than along the shore where the cusps were built, and so no cusps were formed.

The system of cusps continued in existence for about an hour. Then the wind began to freshen and to veer slightly and within a few minutes the larger waves had completely obliterated the series and the beach was again smooth.

A few days later careful observation of a steadily rising sea on Lake Michigan permitted a repetition of the observation of the cusp-building process. In this case the waves had partly cut away a former beach ridge, thus forming a cut bank about 2 feet above the water. As the waves, which were very regular, rose higher and higher the formation of cusps was started, but because of a lessening of the wave height was not completed. A series of five or six cusps was started and two were quite well formed. Had we happened along half an hour later they probably would have been mistaken for partly obliterated old cusps. These two instances were the only ones in which the actual building of cusps of this class was observed. However, now that the process was known, further study of cusps of this class proved very fruitful. By visiting the beach regularly and keeping a record of the behavior of the wind it was possible to learn much of the life-history of the cusps without actually being present at their birth.

As is evident from a consideration of the causal processes, the size and spacing of cusps depends to a great extent on the height and

length of the waves. The cusps form with equal readiness whether the waves move in to the shore perpendicularly or at an oblique angle. With waves of equal height and the same shore conditions they will be more widely spaced when formed by an oblique system. This is because the initial breaks are farther apart and the parabolic movement of the water in the breaks occupies a wider space.

The central ridge which is nearly always well defined in cusps of this class, will point in the newly formed cusps in the direction from which the generating wave system came. However, a later system of waves from another direction may, through erosion, change the direction of this ridge to correspond to the direction of the new wave system. This reshaping makes it difficult to determine, unless the recent history of the wind and waves is known, whether the cusps under observation belong to the present or a former generation. This is made the more confusing because this reshaping can be accomplished either by a considerably larger or by a smaller wave system.

Of course old cusps are found in all conditions of disintegration, as has been described by numerous observers. A system of smaller waves coming in at a new angle may cut off the apexes of a series of large cusps and so form miniature cliffs near their outer ends. Again a larger system of waves may work over the material in a smaller system, re-form the ridge, and form a new system of larger cusps. The speed with which this occurs has led some observers to think that there is a direct genetic connection between the two. Actually the first system is wiped out and the new formed without regard to the original spacing.

In one case observed on the Lake Michigan beach a calm followed the building of a series of cusps. The next wind increased gradually and built up a new smooth beach ridge in front of the line of cusps, thus leaving them a few feet inland.

It might be thought that cusps could be caused to form by making artificial breaks in a beach ridge. Johnson[5] speaks of attempting this on one of the Lake George beaches, and probably many investigators have attempted the same thing. The difficulty lies in the exact adjustment necessary between the height of ridge, spacing of

[5] *Ibid.*, p. 471.

the openings, and the height, regularity, and continuance of the wave system. If the spacing of the openings is not in adjustment with the waves, or if the waves are a little too large or a little too small, they will proceed to close the openings by the process of beach-drifting. Artificial formation of cusps in this way may not be impossible, but would probably require almost infinite patience under natural conditions, although it is possible it might be done rather easily in a large tank with the right apparatus. Mr. J. M. Caldwell,[6] junior engineer with the U.S. Waterways Experiment Station, saw cusps form by the breaching of the beach ridge during the operation of a model used for studying conditions at the mouth of Ballona Creek on the coast near Los Angeles, California.

One observation made the past summer perhaps also indicates the possibility of artificial formation. While the boats were being stored at the White Lake Yacht Club at the end of the season, five small boats that had been lying in front of the clubhouse with their bows drawn up on the beach ridge were all shoved off at the same time. A regular system of waves about a foot high had been coming in for several hours with their axes nearly parallel to the beach. The ridge, which was smooth, had been built up by a somewhat higher sea the previous night. In this case the indentations left in the ridge by the keels of the boats allowed the waves to break through, and in a minute or two four fairly good cusps had formed. They were rather short and blunt, but they had the definite cusp ridges. However, the series was not quite in adjustment with the wave system and in the next half-hour the cusps had changed to shapeless mounds.

Several observers have stated that some cusps of this class are short and broad whereas others are long and slim and may have either high or low ridges. These differences are due to varying conditions of the beach and the waves, including such factors as the supply of material, depth of water near the shore, and the height, spacing, and velocity of the waves.

Many observers have emphasized the uniform spacing of cusps. Jefferson,[7] however, was impressed with their lack of regularity.

[6] Private communication.

[7] M. W. S. Jefferson, "Beach Cusps," *Jour. Geol.*, Vol. VII (1899), p. 238.

There is adequate basis for both views. Along a straight shoreline with uniform conditions the distances between cusps may not vary more than 2 or 3 inches in 8 or 10 feet. Such exact spacing does not usually continue for more than six or eight cusps, and the measurement of a whole series generally shows a rather wide variation.

Measurements of the small cusps that were seen forming on Crystal Lake were as follows: 1.7, 1.6, 1.6, 1.9, 1.4, 1, 1.3, 1.6, and 1.4 feet. There was then a break of about 6 feet, caused by change in direction of the shoreline, and then the line of cusps was continued: 1, 1.3, 1.3, 1.7, 1.4, 1.7, 1.1, and 0.9 feet. Here there was a break of 5 feet, caused by shallow water in front of the shoreline. This was followed by a short series measuring 1.4, 1.4, and 1.3 feet. A casual observation would have given the impression of uniformity, yet in the first group was a variation of 90 per cent and in the second of over 70 per cent.

During the summer numerous cusp series of this class were measured with approximately the same result. A series measured on the shores of Silver Lake was as follows: 4.4, 6.4, 7, 7, 6.6, 6.4, 6.3, 6.3, 5.4, 5, 4.6, and 6 feet. Here there is a difference of 2.6 feet between the shortest and longest space, which is about 59 per cent of the smaller. Five sets measured from south to north on the shore of Lake Michigan near the old outlet of White Lake gave the following: 21.7, 30.5, 34.5, 17.8, 19.8, and 21.4 feet—a variation of close to 94 per cent. After an interval of 69 feet a second series gave the following: 16, 14.6, 11.4, 10.6, and 14.4 feet, with over 51 per cent variation. Four hundred and sixty feet farther to the north was the third series: 13.4, 11.2, 16.2, 10.9, 12.2, 13, 15.9, and 14.9 feet. This is a variation of about 49 per cent. After an interval of 216 feet another series gave 12, 11.8, 14.7, 15, 13.2, 13.9, 12.9, 13.4, 15.2, 15.5, 13.5, 11.6, 12.2, 13.4, 13.4, 16, and 16.2 feet. This series was quite regular for so long a one—only 40 per cent variation. Seventy-five feet farther was a fifth series giving a variation of 42 per cent as follows: 11.5, 13.2, 16.2, 14.5, 13.8, and 14.4 feet.

The cusps in the foregoing series were for the most part nearly equilateral, measured about 3 feet across their bases, and were 6–8 inches high. They were formed by a sea from the southwest, and the ridges of the cusps pointed southwest to west-southwest. The line

of the beach was north and south. About three weeks later on the same shore the following measurements were made of a cusp series formed by waves from the northwest: 16, 15.5, 16, 14.5, 8.7, 11, 16.3, 13.5, 18.8, 20.5, 13.1, 8.3, 8.7, 11.6, 10, 15.2, and 12.4 feet. This gave the greatest variation of any series measured, 147 per cent. Farther to the south another series of cusps was built by the same waves on a beach whose shoreline was curved so its direction changed from southwest-northeast at the south end to north-south at the north end. Measuring from the south gave the following spacing: 10.6, 9.3, 8.9, 7.4, 9.4, 12.3, 14, 13.3, 15.6, 12.7, 16.3, and 17 feet, thus showing a greater distance between the cusps as the waves came on the shore at a more oblique angle.

These investigations were made on tideless waters. However, there is no reason to think that the processes would be different where tides are present. All that seems necessary is that the waves and the materials of the beach be in the proper adjustment to each other. This, in general, would seem to require on a rising tide a slightly decreasing height of wave and the reverse on a falling tide. It is evident that only such cusps as happened to be situated near the upper limit of high tide could be preserved for any considerable length of time.

EOCENE GLACIATION IN SOUTHWESTERN MONTANA[1]

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ABSTRACT

The Black Butte till is described and tentatively correlated with the Ridgeway and Gunnison tillites of Colorado. It underlies mid-Tertiary volcanics and rests upon upturned truncated Lower Cretaceous sediments.

INTRODUCTION

In 1915 W. W. Atwood[2] published the first description of Eocene glacial deposits, Ridgeway tillite, in North America and suggested the possibility of extensive Eocene glaciation throughout the Cordilleran province. In the same year C. W. Drysdale[3] made a similar discovery in southern British Columbia. In consonance with W. W. Atwood's prediction, other tillites[4, 5] were described from areas in southern Colorado in 1917 and 1926. This paper considers a till deposit in southwestern Montana, the Black Butte, about intermediate in distance between the Colorado and British Columbia deposits. The Montana deposit occurs in the southeast portion of what was called Jefferson Range in the Three Forks folio. The north part of this range is now known as Tobacco Root Mountains. The south half of the range is divided into two divisions which merge at Baldy Mountain near Virginia City; one division is called Snowcrest Range, the other Gravelly Range. Gravelly Range extends southward 40 miles from Virginia City to the northern side of Red

[1] Published with the permission of the Director of the Montana Bureau of Mines and Geology.

[2] "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Surv. Prof. Paper 95-B* (1915).

[3] "Geology of Franklin Mining Camp, British Columbia," *Canadian Geol. Surv., Mem. 56* (1915).

[4] W. W. Atwood, "Another Locality of Eocene Glaciation in Southern Colorado," *Jour. Geol.*, Vol. XXV (1917), pp. 684–86.

[5] W. W. and W. R. Atwood, "Gunnison Tillite of Eocene Age," *ibid.*, Vol. XXXIV (1926), pp. 612–22.

Rock River Valley. It is drained on the west by Ruby River and on the east by Madison River.

The field work on which this paper is based was done during the summer of 1935 as part of a general study instituted by the Montana Bureau of Mines and Geology on the origin, distribution, and gold content of the gravels in Gravelly Range. The area was revisited during the fall of 1936 and the summer of 1937. The type section of the Ridegeway tillite was also visited during the summer of 1937 for the purpose of making a direct comparison. Acknowledgment is made of helpful criticism given in the field by Dr. Eugene S. Perry, Montana School of Mines.

PHYSICAL GEOGRAPHY

The name Gravelly Range connotes a physical characteristic of these mountains. The "gravels" are, for the main part, glacial deposits of various ages. They vary in thickness from a thin veneer to as much as 200 feet. In addition to those of early Tertiary age, three distinct stages of Pleistocene glaciation are recognizable.

Gravelly Range has an average elevation of 8,500 feet and attains a maximum elevation of 10,546 feet. The most conspicuous topographic features are Black Butte near the south end of the range and Baldy Mountain near the north. The west flank slopes gently toward the drainage of Ruby River, a tributary of Jefferson River. Madison River forms a natural boundary on the east, and its tributaries have cut deep V-shaped valleys into Paleozoic and pre-Cambrian strata forcing the divide to migrate westward. The rugged east side is in sharp contrast to the less dissected west flank which is formed on a 12° dip slope of Cretaceous rocks. The west fork of the Madison heads into the south end of the range and, by simple stream piracy, has captured many of the tributaries which formerly drained south into Red Rock River.

DESCRIPTIVE GEOLOGY

Structure.—The structure of the region has had much to do with the preservation of the Black Butte till. A large normal fault forms the east escarpment of Snowcrest Range, a range which merges into Gravelly Mountains on the north at Baldy Mountain. This near-by

mountain front retarded erosion on the west flank of Gravelly Range until Ruby River cut a gap at Home Park by headward erosion in late Pleistocene time and captured much of a southward-flowing drainage system. Consequently, the west flank, as well as the present crest of the range, has not been deeply dissected and many of the unconsolidated deposits, Tertiary and Pleistocene, are still in place.

Stratigraphic section.—Rock strata cropping out in this area range in age from Archeozoic to Cenozoic inclusive. The pre-Cambrian rocks are primarily garnetiferous gneisses of the Pony series and schists of the Cherry Creek series. Occasionally pre-Cambrian marbles and quartzites of the Cherry Creek form extensive outcrops. The outcrops of gneiss and schist are limited to the margin of the eastern flank and the north end of Gravelly Range from Baldy Mountain to Virginia City and Alder.

The Paleozoic section, common to southwestern Montana, composed primarily of limestones, shales, and quartzites, is exposed from the present crest of the range eastward into the deeply dissected area; also on Baldy Mountain and west in Snowcrest Range, which for the most part consists of the Madison, Amsden, and Quadrant formations.

Mesozoic rocks form the gently dipping east face of the range and are composed primarily of sands and shales which in many places also form the crest of the mountain range. The Tertiary rocks are mostly volcanics and occur in isolated patches as erosional remnants of former more extensive flows, except in the vicinity of Virginia City where they cover an area of approximately 50 square miles. The Tertiary extrusives consist of white-to-pink tuffs overlain by dark basalt. They rest upon an erosional surface which truncates the up-turned beds of pre-Cambrian, Paleozoic, and Mesozoic age.

The three Pleistocene drift sheets represent the Wisconsin and two older stages. The oldest of the drifts occurs on hilltops and ridges as isolated remnants of a once more extensive deposit.

DESCRIPTION OF THE TILL

The type locality of the till is on the southwest side of Black Butte (Fig. 1), a prominent physiographic feature that rises 1,000

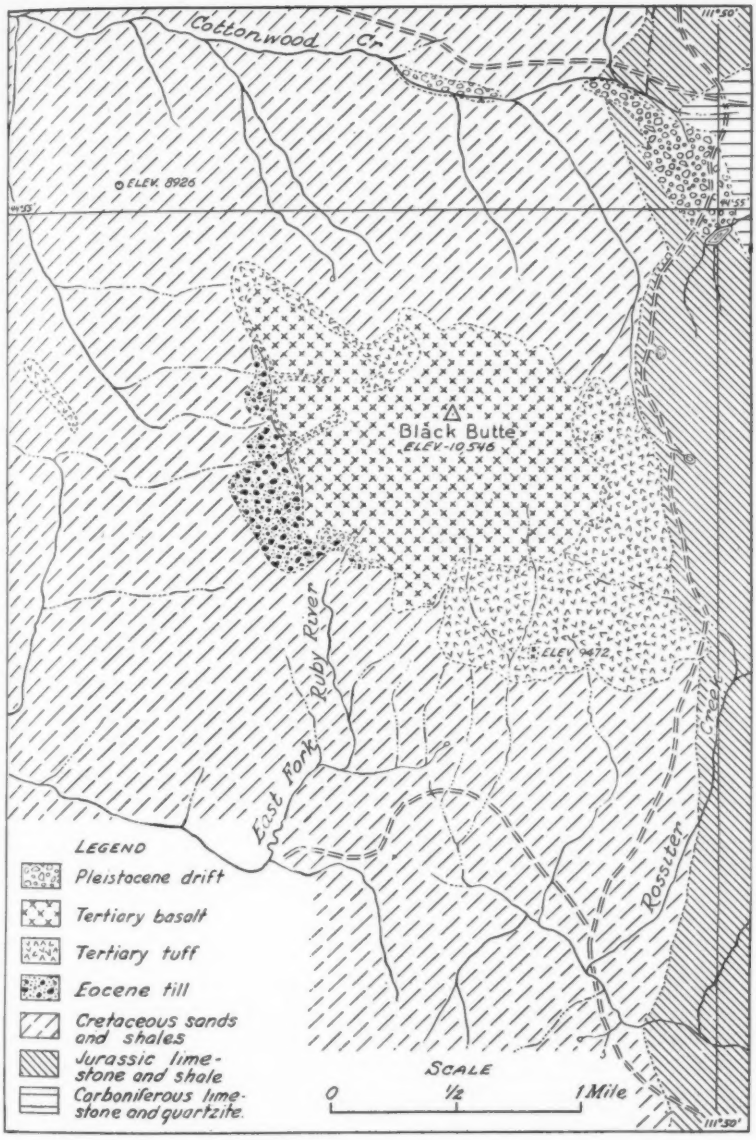

FIG. 1.—Map of Black Butte area showing relationship of the till to overlying Tertiary volcanics and underlying Cretaceous sediments.

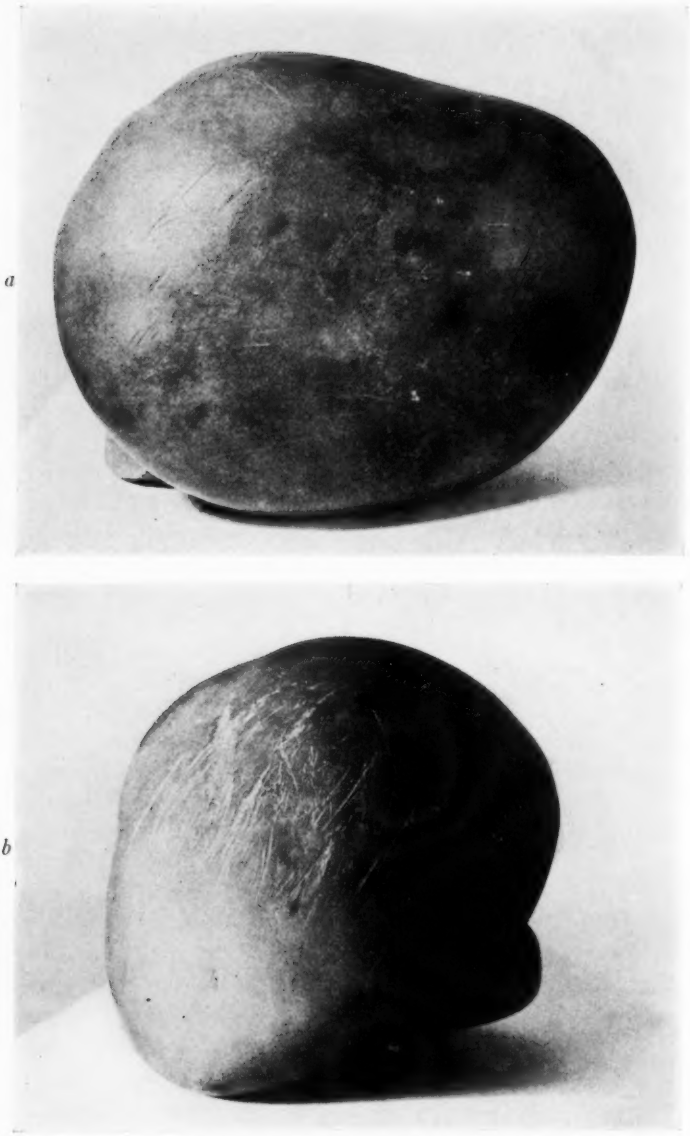

FIG. 2*a*, *b*.—*a*, Striated quartzite cobble; *b*, opposite side of cobble shown in *a*. ×½

feet above the surrounding area. It is composed chiefly of columnar basalt. In places around the margin of the butte white unconsolidated tuff attains a thickness of 200 feet or more. The tuff underlies and is therefore older than the basalt. At some points the basalt rests directly upon Mesozoic sands and shales. Isolated remnants of the volcanics occur throughout Gravelly Range.

The glacial deposit is unconsolidated and is composed of rocks ranging in size from clay particles to boulders 5 feet in diameter. The large pieces are mixed with fine sand and silt, the whole representing typical heterogeneous glacial till. Irregular, faceted stones

FIG. 2*c*.—Striated piece of white quartzite. ×½

and beautifully striated pebbles and cobbles are present. Striated specimens are most frequently found at the south end of the deposit. Water-worn pebbles and cobbles are common and most prevalent near the base of the formation, but these contain some of the best striations. Cobbles of quartzite seem to be most commonly striated and, interestingly, some of the rounded and polished specimens contain the deepest and most numerous striations (Fig. 2 *a*, *b*).

The till contains igneous, metamorphic, and sedimentary material. It is made up of the following in the approximate order of their abundance: white-to-pink quartzite, dark-gray quartzite, pegmatite quartz, chert, gneiss, red quartzite, sandstone, orthoclase, porphyry, and yellow quartz. Limestone and basalt are entirely absent. The material has been derived primarily from the pre-Cambrian metamorphics. Any Paleozoic limestones which may have been incorporated in the till have been completely leached.

AGE AND CORRELATION

There is abundant evidence throughout the Cordilleran province that the close of the Mesozoic era was marked by profound crustal movements during which the Rocky Mountains were first uplifted. That glaciation occurs at such times of deformation and regional uplift has long been an accepted fact among geologists, and the discovery of the Ridgeway tillite in 1915 conformed with this general theory. The Paleozoic and Mesozoic rocks in Gravelly Range were uplifted and folded during the Laramide orogeny. Dissection was continuous throughout the uplift, and in some places thousands of feet of sediments were removed. As dissection went on it is safe to presume that glaciers existed in many of the higher areas. A reconstruction of the old profile of Gravelly Range suggests that the east side of that range attained an elevation of approximately 12,000 feet. It is certain that the source of the Black Butte till was to the east and north of its present position.

The age of the Black Butte till must be determined through a study of the overlying and underlying formations. The till rests upon an erosional surface which truncates rocks that were tilted and folded during the Laramide orogeny (Fig. 3). This makes it evident that the till is Eocene or younger. The overlying formations consist of extrusives, tuffs, and basalts, and the determination of their exact age is the most important problem in determining the age of the Black Butte glaciers. There is some indirect paleontological evidence concerning the age of these volcanics.

During most of middle Tertiary time large lakes existed in the intermontane basins of southwestern Montana. During the same time volcanic activity extended over a wide area and resulted in extensive lava flows and tuffaceous deposits. The sediments which accumulated in the intermontane lakes are collectively known as the Bozeman beds, ranging in age from lower Oligocene to probable Pliocene.

Immense showers of volcanic dust settled in the lakes that occupied the main intermontane valleys, as well as on the upland areas. The ash that is associated with the lower Bozeman "lakebeds" is of the same origin as the tuff which underlies the basalt.

In Madison Valley east of Gravelly Range the pure pumiceous dust is interbedded with the lower Bozeman beds, whereas the upper beds consist largely of impure ash washed into the lakes from the surrounding country. The tuffs on the upland areas were probably formed contemporaneously with the white ash in the basal part of the Bozeman beds. Oligocene and Miocene fossils, mainly vertebrates, have been found in these "lakebed" deposits. There-

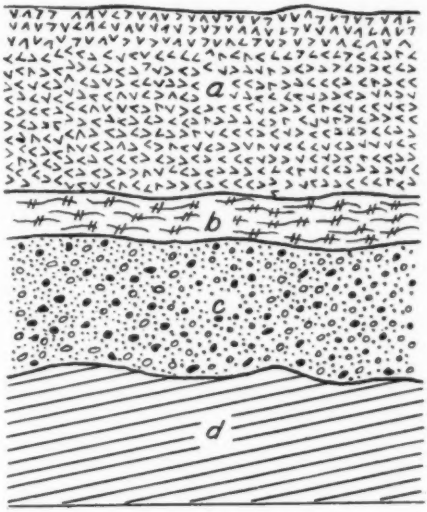

FIG. 3.—Geologic section on southwest side of Black Butte: *a*, basalt; *b*, andesitic tuff; *c*, Black Butte till; *d*, Cretaceous sands and shales.

fore, the age of the tuffs overlying the Black Butte till is certainly mid-Tertiary, probably Oligocene, as indicated by the relationship of the tuffs to the lower Bozeman beds which contain Oligocene fossils. Physiographic studies throughout the Rocky Mountains by many workers show that no mountain ranges existed in Oligocene time comparable in elevation to the earlier Rockies. The Black Butte till should, therefore, belong to the RockyMountain generation of Eocene time and is probably to be correlated with the Ridgeway glacial stage of Colorado.

SIZE OF EOCENE GLACIERS

Atwood has shown that the Ridgeway till was transported for a distance of 40 miles and suggests that the glaciers were of a piedmont or local ice-sheet type. The Black Butte till was transported at least 10 miles from the northeast. The characteristics of the Eocene tills do not indicate deposition by small valley glaciers, but predicate the existence of larger ice bodies such as local ice sheets or large piedmont glaciers. The writer is in agreement with Atwood's suggestion that the Eocene glaciers in the Rocky Mountains were probably more extensive than the Pleistocene glaciers.

RECENT DEPOSITION OF SALT FROM GREAT SALT LAKE

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ABSTRACT

Great Salt Lake has precipitated sodium sulphate each winter and redissolved this salt during the early spring as long as observations have been made. But within the last four years summer precipitation of sodium chloride has also taken place as an accompaniment of the unprecedented low level of the lake. The sodium chloride returns into solution during the early winter, completing a spectacular annual cycle of salt precipitation and solution. Winter precipitation of sodium sulphate is caused by the cooling of the water; summer precipitation of the chloride is caused by the annual reduction in volume of the lake, a result of heavy summer evaporation and reduced inflow during this season. A large tabular deposit of almost pure sodium sulphate lies buried in the beach sands along the southeast shore of the lake and may be related in its formation to past winter precipitation of this salt similar to that now being observed.

INTRODUCTION

Precipitation of sodium sulphate from the waters of Great Salt Lake during the winter has been taking place for as long as observations have been made. But during the summers of 1934, 1935, 1936, and 1937, for the first time, so far as definitely known, the lake has also precipitated sodium chloride upon its bed in the summer time. Immense masses of halite cover the bed of the lake through the fall months and then gradually return into solution as winter advances —a time which also marks the beginning of sulphate precipitation. In turn the precipitated sulphate, which accumulates in great quantities during the coldest months, redissolves when the lake warms in early spring. The two salts thus alternate in covering the lake bed, leaving it bare during only three or four of the spring and early summer months. In the last four years during which summer precipitation of sodium chloride has occurred, the winter precipitation of sodium sulphate has been greater than before.

HYDROLOGY OF THE LAKE

This unprecedented precipitation of sodium chloride and the abnormally great precipitation of sodium sulphate which took place during the last four years result from reduction in volume of water

indicated by a secular lowering of lake-level which began in 1924 and culminated in the winter of 1935–36. Shrinkage of the lake was caused by unusually low precipitation within the area tributary to the lake. During this period from 1924 to 1936 the lake surface sank from an elevation of 8.2 to −3.1 feet on the Saltair gage, these figures representing the highest stage in the last sixty-year period and the lowest stage within historic time, and involving a recession of 11 feet.

The lake being in a closed basin with no outlet, its volume and level are determined by inflow and evaporation acting in opposition to one another. Water reaches the lake from direct precipitation, from the measured inflow of three important river systems, some unmeasured surface inflow, and by lesser amounts of seepage directly into the lake. Water from these sources enters the lake principally between November and May and the lake then rises on the average of $1\frac{1}{2}$ feet. During the summer there is very little inflow, while, on the other hand, evaporation is great and the lake consequently recedes in stage. In each year from 1924 to 1935 the summer lowering exceeded the winter and spring rise by an average of 1 foot. Evaporation from the lake is less than from a fresh-water body of similar location by perhaps 30 per cent, owing to the salt content. The temperature of the surface water of the lake varies from 85° F. in the summer to 25° F. or lower in the winter. The coldest time of the year is late January and early February; the warmest is July and early August. Because the lake is shallow and stirred to its bottom by every passing storm, there is little temperature difference with depth. It has a maximum depth of 30 feet and an average depth of 15 feet at a stage of zero on the Saltair gage.

The normal stage of the lake is near 4 feet on the Saltair gage, at which the lake has an area of 1,090,000 acres. Within the last five years the lake has had an average stage near −2.0 feet on the Saltair gage, an area of 715,000 acres, and a volume of about 12,000,000 acre-feet.

SALTS OF THE LAKE

The total salt content of the lake is about 6,500,000,000 tons The proportions of different salts are shown in Table 1.

As the lake lowered from 8.2 feet to −1.0 feet its salt concentra-

tion increased from 18 per cent to saturation, which is approximately 30 per cent. During 1936, in consequence of increased precipitation, the lake rose ½ foot and repeated this rise in the spring of 1937. For this reason, halite precipitation during the summer of 1937 was meager. It is popularly supposed that a several-year period of higher precipitation has begun, and, if so, salt precipitation in the summer will cease.

It will be recognized that all the salts in the lake are very soluble under all temperatures, with the exception of sodium sulphate,

TABLE 1

Ion	Percentage of Ions	Salt	Percentage of Salts
Cl	55.5	NaCl	76.60
SO_4	6.6	Na_2SO_4	10.00
Na	33.5	KCl	3.05
K	1.6	$MgCl_2$	9.80
Ca	0.2	$CaCl_2$	0.55
Mg	2.6		

whose high solubility at warm temperatures decreases markedly in cold water. It is this property of sodium sulphate which has caused it to be precipitated during the coldest period of the year, at all stages of the lake, even before the recent low stages.

WINTER PRECIPITATION OF SODIUM SULPHATE

Winter precipitation of sulphate from the lake is affected by stage as has been stated, but is probably affected to a more marked extent by coldness of the season. Usually precipitation has first become noticeable early in December. In two of the recent years very large bars of the salt have been built by the waves in the shallow, shore waters of the southeast portion of the lake. The bars, which reached their greatest extent in early February, have stretched for many miles along the lake shore and over much of their length have been 3 to 4 four feet in depth and perhaps 200 feet wide. The tops have been about 1 or 1½ feet above water surface. Precipitated sulphate is in the form of the decahydrate, which has a specific gravity of 1.5 and therefore loses much of its apparent weight in the water of the

lake, which has a specific gravity as high as 1.22 at times of greatest concentration. Waves thus easily move the crystals. Masses of sulphate have been reported to have been observed floating some distance from shore. Perhaps they contained entrapped air or the sulphate was enmeshed with fresh-water ice.

The entire bed of the lake becomes coated with sulphate crystals in the winter, and thick layers of the salt adhere to piles, bottoms of boats, rocks, or other objects submerged in the water. During

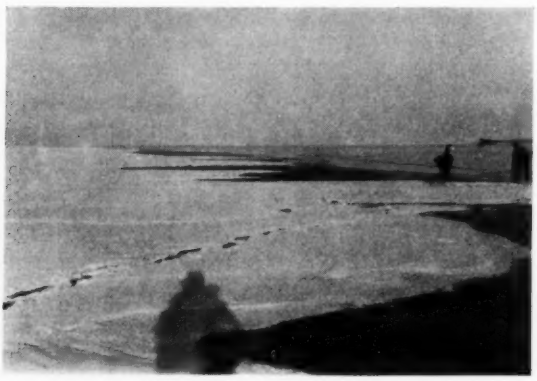

FIG. 1.—Sodium sulphate bar formed on the shore of Great Salt Lake in the late winter of 1933–34. The view shows the lagoon side of the bar; the lake is to the left. One man is standing in the soda to his thighs at the edge of the portion of the bar above water while the other is climbing up on more solid parts of the bar.

times of coldest lake temperatures only a very few days are required for a coating of several inches of sulphate to accumulate on objects in the water. The sulphate precipitates readily on such moving objects as the rotating propeller of a boat.

While submerged in the water or close enough to the water to be kept wet, and except where disturbed by the waves, the sulphate deposits are solid though not very hard, and soft crystal masses adhere to objects with moderate tenacity. The bar deposits are composed of loose crystals which do not cake readily, resembling rather closely a snowbank. If crystals of sulphate are removed from the water and placed in a warm place to dry, they lose most of their

water of crystallization and crumble to a fine white powder. Analyses show about 2 per cent chloride as their chief impurity which is derived in part from the lake water adhering to the crystals when they are removed from the water.

The deposited sodium sulphate is quickly taken back into solution when the weather moderates and the lake warms a few degrees. This usually has occurred by the end of the first week in March.

FIG. 2.—General view along the bar of sodium sulphate formed near shore in Great Salt Lake during the late winter of 1933–34. The lake is to the left, and a lagoon is on the right.

SUMMER PRECIPITATION OF SODIUM CHLORIDE

Sodium chloride precipitation during the first three of the last four years has begun during the early or middle summer and continued to late autumn, or during that time when evaporation has greatly exceeded inflow and the lake level has been falling. Precipitation of chloride in the summer of 1937 did not occur until later in the season and at a somewhat lower stage, owing probably to a change in the solution equilibrium as the temperature of the lake lowered. Table 2 gives for each summer approximate dates and gage heights of the lake at which precipitation of halite became general.

It is to be noted that the lake reached saturation for summer temperatures when its stage lowered to near −1.0 on the Saltair gage. The lake reached this low level at the lowest point of its

recession in 1905 but did not again go below this level until 1934. No widespread precipitation of salt was noted during 1905.

During the years when halite precipitation has been great, the entire bed of the lake has been coated with the salt which by late fall has become 3–6 inches thick near shore but somewhat thinner in deep water. The layer of salt has extended some distance up on the gently sloping beaches to an elevation as high or higher than the level of the lake when precipitation began for the year. The action of the wind in raising the water surface on the leeward shore during a storm, as much as 2 or even 3 feet, has been the cause

TABLE 2

Year	Date Halite Precipitation Began	Stage of Lake When Precipitation Began (in Feet)	Seasonal Gage Heights	
			Highest (in Feet)	Lowest (in Feet)
1934	July 15	−0.95	+0.4	−2.1
1935	June 15	1.00	−0.8	3.1
1936	July 20	1.20	−1.0	2.6
1937	Sept. 7	−1.60	−0.8	−2.3

of salt precipitation on the beaches above normal water level. The deposit of salt precipitated during 1935 was thicker than in the other years and precipitation began earlier.

Each winter all the sodium chloride is taken back into solution as a result of the addition of fresh water from increasing rainfall which usually begins in midautumn, and also, no doubt, because the precipitation of sodium sulphate changes the solution equilibrium of the water with respect to sodium chloride. Little sodium chloride remains in evidence by midwinter, when the precipitation of sulphate reaches its greatest amount. By early spring all of both of these has returned to solution.

Halite deposits are hard and covered with characteristic cubical crystals. The salt forms rapidly upon any submerged object, even on a rapidly rotating propeller of a boat or within the impeller of a centrifugal pump in operation. Upon piles it has formed large bulbous masses three feet and more in radius near the water surface

during a season. Such a deposit tapers to a few inches in thickness a few feet below the surface. Along trestles of the Lucin Cutoff, such masses of salt have been removed with air hammers at con-

FIG. 3.—Summer precipitation of sodium chloride on piles of a trestle in Great Salt Lake during the summer of 1935.

FIG. 4.—View of sodium chloride accumulation on a beach of Great Salt Lake during the late fall of 1935. Earlier in the season the water covered the beach area shown in the picture and at that time formed the girdles of salt around the piles.

siderable expense to avoid damage to the trestles by waves. The salt crust of the beach has been gathered and marketed for stock-feeding, ice-cream salt, and other uses. It is relatively pure.

Where perennial fresh-water streams enter the lake, the water near their mouths is kept above the saturation point both in summer and winter, and salt precipitation has not occurred within the limited

FIG. 5.—Salt accumulation on the propeller of a boat. The salt accumulated during twenty hours' cruising on the lake. The propeller is on a stern-drive and was only in the water during its actual use. The tendency for salt to collect on the back side of leading edges of the propeller is illustrated.

zones where this freshening influence is effective. When the lake is calm, water from these streams spreads out in thin sheets, an inch to several inches thick, over the top of the salt water for considerable distances before mixing. As a result evaporation and concentration

of the underlying salt water is prevented and previously formed salt deposits are sometimes dissolved. The quick disappearance of halite in the late fall in some localities is partly due to this action. But whenever the surface of the lake is disturbed by a storm the fresh water is thoroughly mixed into the lake.

During the period of sodium chloride precipitation, the lake, when calm, will be observed to be nearly covered with very thin, round, crystalline aggregates about $\frac{1}{2}$ inch in diameter, which when disturbed break from the surface and sink. Also at this time, with proper illumination, the water of the lake will be seen to be permeated with fine crystals. Great Salt Lake, which is naturally less clear than ordinary fresh-water lakes, becomes practically opaque in thicknesses of about 6 feet during times of salt precipitation. During recent years it has had its normal transparency only in the late spring.

SHORE DEPOSITS OF SODIUM SULPHATE

Probably closely related to salt precipitation from Great Salt Lake is the occurrence of shore deposits of sodium sulphate in a single buried layer along the south and southeastern shores of the lake. The beach in this vicinity has a gentle slope of a few inches to a foot in a hundred feet and is formed from calcareous oolitic sand characteristic of the lake and generally accepted in itself as being a chemical precipitate from the lake. The sodium sulphate deposit is buried in beach sand from a few inches to about 4 feet and has a sharply marked top and bottom. Its thickness is as much as 4 or 5 feet. The area covered by the sulphate deposits extends from about the high-water line of the lake to a line about coincident with the lowest of recent water lines, being a band from 2,000 to 8,000 feet wide and extending a number of miles along the shore. The thinner sand covering is at the lakeward edge of the deposit. The sulphate apparently rests on soft silts entirely different in character from the sand above. The sulphate in itself is reported to be relatively pure but it is mixed with somewhat less than an equal amount of calcareous sand. Piles for structures built within the sulphate area cannot be driven but are jetted with steam. Since the lake water has receded from the sulphate area, numerous small sink holes which appear to be vertical channels through the layer resulting from

fresh-water solution have been observed in the sulphate. They are marked on the surface where the sand has slumped into them and left small craters.

The origin of the sulphate stratum has not been explained. Conditions suggest that precipitated sulphate crystals throughout winters of past ages have become buried in littoral sand drift and there protected from re-solution. The occurrence on the southeast shores is apparently the result of prevailing winter storm-winds which blow southeastward over the lake. The sulphate bed has probably been modified by water moving in the sand below and over it.

Several organizations have contemplated mining the sulphate shore deposits or obtaining sulphate from the bars annually formed in the lake. One has built a refining plant with a daily capacity of one hundred tons and is about to begin recovery of sulphate from the shore deposits. The refining operation consists of dissolving the salt, separating out the sand in a classifier, and salting out the sulphate in an evaporator at a temperature high enough to yield the anhydrous salt. The shore deposits yield remarkably pure sodium sulphate.

Recovery of sodium chloride from the lake water is an old and well-established business and has been accomplished by pumping water from the lake and subjecting it to solar evaporation. Gathering of salt crust from the shore in recent years has not affected this business.

THE LOESS OF THE MATANUSKA VALLEY, ALASKA

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ABSTRACT

In 1935 the colonization of a part of the Matanuska Valley in south-central Alaska was undertaken by the federal government. The agricultural land, where the soil is fertile and deep, is limited in extent. The soil is loess, which is being deposited even today, and clearly demonstrated is the part that glaciation may play in the formation of such deposits.

INTRODUCTION

The colonization of the Matanuska Valley agricultural land, one of the federal relief projects, started in the spring of 1935, when two hundred families from the submarginal and drought-stricken areas of the midwest were moved to the Matanuska Valley in south-central Alaska. This agricultural area, commonly known as the Matanuska Valley, is at the junction of the Matanuska and Knik valleys, and a few miles west the combined valleys merge into the broad Susitna Valley. Especially adapted to agriculture is an area approximately 10 by 15 miles in extent, at an elevation of from 200 to 500 feet above sea-level, and encircled on three sides by snow-capped mountains of the Talkeetna and Chugach ranges, which rise up to 6,000 feet in height (Fig. 1).

It was early recognized that the soil in this restricted area was fertile and deep, and in 1916, when the government-owned-and-operated Alaska Railroad was constructed through the district, some of the land had already been settled. Areas of rich and deep soil in this part of Alaska are not numerous; because of severe glaciation, there are practically no residual soils, and bedrock is usually mantled by glacial deposits, which in only a few localities are suitable for intensive farming.

The Matanuska soil is of eolian origin, being deposited even today, in some localities, at a rate of several inches in the last twenty years. It is originating under conditions somewhat similar, although on a much smaller scale, to those postulated for the loess formation in

some of the midwest states, and it clearly demonstrates the efficacy of glaciation in the formation of eolian deposits.

TOPOGRAPHY AND GEOLOGY

The topography of the agricultural area is largely of glacial and glacio-fluviatile origin. Several well-defined terraces upon which are a few topographic depressions border the Matanuska River. To the north and northwest, at a higher elevation, are more poorly defined

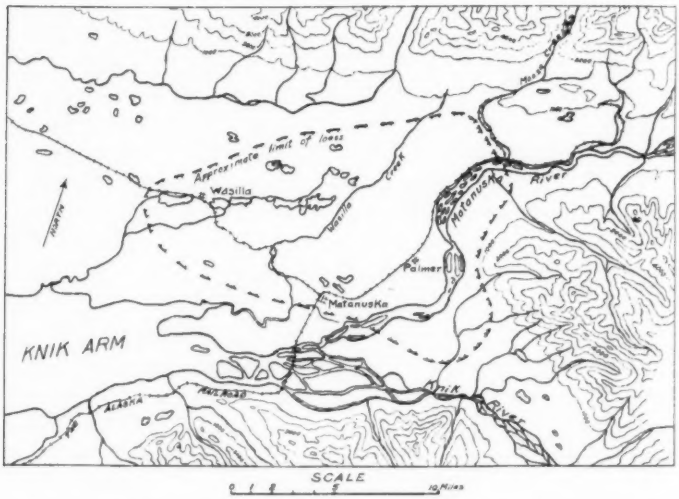

FIG. 1.—The Matanuska agricultural district showing the area of loess deposition

terraces with numerous depressions. Still farther to the northwest the topography is very irregular, with long sinuous ridges and many lakes. Exposures of the material forming this topography are few because of the depth of soil and vegetation, but it is probable that both eskers and lateral moraines are present.

Extensive well-drilling for the agricultural colony has shown that bedrock is a few to over 150 feet below the surface; the average depth is about 80 feet, and surface exposures are few. The oldest formation is a greenstone of pre-Cretaceous age, consisting principally of altered basic flows with a few interbedded sediments. These rocks

form a large part of the Chugach Mountains on the north and south sides of Knik River and in a few places protrude through the unconsolidated deposits as small ridges and buttes. Cretaceous sandstone, shale, and conglomerate are exposed along the bluffs of the Matanuska River above Palmer. The youngest consolidated formation is Eocene shale, sandstone, and conglomerate with interbedded coal seams. It is exposed along the Matanuska River above Palmer, on Moose Creek, on the south flank of the Talkeetna Mountains, and probably under a large part of the agricultural area. Overlying the consolidated rocks are the glacial deposits. Near the river the terraces are composed of rudely stratified gravel, sand, and silt. The depressions in these terraces have been formed by the melting of blocks of ice that were covered or surrounded by the glacial outwash detritus. The glacial deposits are in turn mantled by loess.

THE LOESS

The soil-forming loess is thickest in the vicinity of Palmer (Fig. 1), where it sometimes is over 20 feet deep. It thins out toward Wasilla, the Talkeetna Mountains, and Moose Creek. Close to the Matanuska River it is sandy, while on the west and northwest margins it is of much finer texture. The prevailing color is gray, buff, or various shades of brown. In road cuts and along the streams, the loess weathers into vertical faces and constantly breaks off in slabs that parallel these faces. Fine laminations are sometimes visible, particularly in the weathered sandy phases (Fig. 2). Irregular horizontal bedding from vegetable material is present in some cuts. A few exposures show several $\frac{1}{2}$-inch bands of volcanic ash that are near or as much as 10 feet below the surface.

Proof of the eolian origin of the soil is conclusive. From the neighboring mountains, in dry weather and even in winter, a pall of dust is frequently visible over Palmer and the surrounding country (Fig. 5). In some localities section corners staked in 1913 were found in 1935, covered with several inches of soil. Zones of decayed and carbonized wood are found as far as 10 feet below the present surface (Fig. 3). Other newly made exposures show root fibers near the surface which grade downward into a zone where the roots are carbonized; still farther downward the root fibers are entirely gone, and

their former presence is indicated only by tubelike casts which impart a vesicular appearance to the loess. The surface of the soil

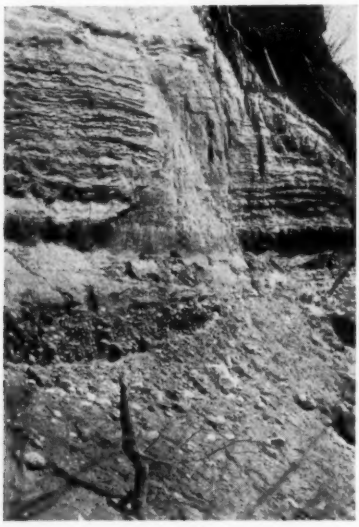

FIG. 2.—Typical weathering of sandy phase of loess and glacial outwash gravel underlying.

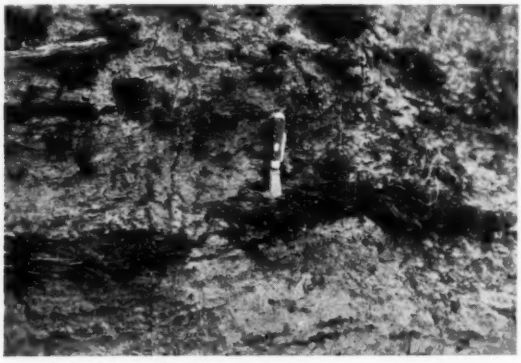

FIG. 3.—Loess-buried brush and limbs about 5 feet below the present surface

roughly parallels the irregular surface of the underlying unconsolidated deposits, further indicating the eolian origin (Fig. 4). Most

of the area was heavily timbered (Fig. 5) prior to the colonization in 1935; this vegetation served as a wind break, and the loess settled into it, but whether the soil will remain with the vegetation removed and the land tilled is conjectural.

FIG. 4.—Two feet of loess (black band at surface) mantling glacial outwash gravel on side of small hill.

FIG. 5.—Haze from dust being carried over timbered agricultural land near Palmer. Taken with Wratten A (No. 25, tricolor red) filter.

SOURCE OF THE MATERIAL

Both the Matanuska and Knik rivers have their source in glaciers. The present front of Knik Glacier is 20 miles, and the Matanuska

Glacier 45 miles, from the junction of the two valleys. Both rivers are typical glacial streams, silt-laden, with many and constantly changing channels and broad flood plains (Fig. 6), so that a supply of

FIG. 6.—Dust arising from the flood plain of Matanuska River at its junction with Knik Valley, which is in the background.

FIG. 7.—Glacial flour being picked up from the floodplain of Matanuska River and spread over the surrounding country.

material is always available for transportation by the wind. The prevailing direction of the wind is down-valley, from off the glaciers, and frequently these currents confined within the relatively narrow

valleys are very strong. The glacial "flour" is picked up, carried to the junction of the valleys, and deposited (Figs. 6 and 7).

The greater part of the loess is carried in from the Knik; on windy days this is visibly apparent. The Knik winds are stronger than those along the Matanuska, and the Knik Valley is straighter, with fewer topographic obstructions. The broader flood plains of the Knik River provide a greater area for the deposition of glacial "flour," and they also receive more such material, as, in addition to being covered by the usual high water, they are inundated for several weeks in the fall by the annual draining of a lake on the side of Knik Glacier. This lake is in a valley blocked by the glacier. Throughout the summer the lake rises and, in the fall, overflows the top of the glacier, quickly cutting a channel through it, and so draining itself within a few weeks, inundating the entire Knik Valley. Sand dunes are numerous on the north side of Knik River in the vicinity of Jim Creek; such dunes do not occur in the Matanuska Valley.

Glaciation, in this case, is aiding the formation of loess by supplying the necessary material—the glacial flour—and by increasing the intensity of the prevailing winds, as the glaciers at the heads of the valleys create high-pressure areas.

THICKNESS OF THE GLACIAL DRIFT IN WESTERN OHIO

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ABSTRACT

In the preparation of this paper twenty thousand well records were examined and six thousand of the significant ones were plotted. The average thickness of the drift in western Ohio is 69.5 feet. Great thicknesses up to more than 530 feet are recorded along the buried valley of the old Teays, which passes in a northwesterly direction through Madison, Champaign, Shelby, Auglaize, and Mercer counties into Indiana. The preglacial Maumee, Portage, Sandusky, Huron, Cuyahoga, and Ohio rivers were tributaries of a large stream which flowed eastward draining the valley now occupied by Lake Erie. A preglacial divide separated western Ohio into three drainage areas—the Erie lowland, the southwestern basin, and the area drained by the old Teays River. In preglacial time the valleys of western Ohio were broad, such as would exist in a region worn down to an advanced stage of erosion. During the Deep stage, which preceded the Illinoian stage, they were deepened considerably.

INTRODUCTION

In 1934 engineers and geologists working on a government project collected one hundred and forty-eight thousand well records for the Ohio Water Conservation Commission. About half of these are from western Ohio. The records include the well-head altitudes and the depth to the ground-water surface and to the bedrock. About one-fourth of the records indicate the depth to bedrock.

Approximately ten thousand well records were obtained from the Ohio State Geological Survey, to which they were furnished by the Ohio Oil Company of Findlay, Ohio. The majority of these are from Wood and Hancock counties, the remainder from Sandusky, Auglaize, Mercer, Wyandot, Lucas, Putnam, and Hardin counties. About twenty thousand well records were examined and six thousand of the more significant ones were plotted on base maps of western Ohio.

PREPARATION OF THE MAP

The map presented in this paper was drafted from the original through the courtesy of Wilbur Stout, state geologist of Ohio. It shows for most wells three figures in a group, the two above the horizontal line representing the minimum and maximum thicknesses, and the one below giving an average of the drift thicknesses

in that particular area. Other figures show the average thickness of the drift at specific points. This method is used because of the impossibility of plotting all the figures. Some areas have few or no records because the government project was abandoned when approximately half of the state was covered. The position of the buried river courses is indicated by the stippled areas. In an earlier publication[1] the buried surface of western Ohio was shown by means of contours and the location of the buried valleys indicated by dotted lines. All well records which do not reach bedrock are indicated by the letter *G*. Bedrock exposures which are numerous throughout the area are not shown on the map.

THE THICKNESS OF THE DRIFT

The average thickness of the drift for all of western Ohio, as computed by the writer from six thousand well records, is approximately 69.5 feet. This is considerably less than the average obtained for north-central Ohio, which is 95.7 feet.[2] The preglacial topography of the Appalachian Plateau in north-central Ohio was rugged—as rough as the unglaciated area in the southeastern portion of the state. A high preglacial divide, in places reaching 1,300–1,400 feet in elevation, extended from Port Washington on the Tuscarawas River through Holmes and Richland counties and was continuous with the divide in Morrow, Marion, Union, and Logan counties, as shown on the map. The general slope of north-central Ohio in preglacial time was toward the Erie lowland, which was then a broad river valley. As the ice sheet pushed southward beyond the Erie lowland, it was forced to pass over rough hilly country which offered increased resistance to its movement. Furthermore, the ice sheet was advancing upgrade toward the divide in Holmes County. This combination of conditions checked the advance of the glacier in the hills on and near the divide, and the ice deposited its load in a comparatively narrow belt between Lake Erie and the old divide, whereas in western Ohio the drift was spread over a larger area in a thinner sheet.

One would suppose that where the terminal moraines are found in

[1] Karl Ver Steeg, "The Buried Topography of Western Ohio." *Jour. Geol.*, Vol. XLIV (1936), p. 928.

[2] Ver Steeg, "The Buried Topography of North-Central Ohio and Its Origin," *ibid.*, Vol. XLII (1934), p. 605.

western Ohio there would be a marked increase in the thickness of the drift. The writer, however, finds it difficult to trace a moraine through western Ohio, using the thickness of the drift as the criterion. If the bedrock surface beneath the glacial drift were uniform in elevation, the thickness of the cover would necessarily be greater where the moraines occur. But the buried surface in western Ohio is not uniform in elevation; in preglacial time this was a rolling country with wide valleys and broad divides. The irregularity of the preglacial surface has been more important in determining the thickness of the drift in western Ohio than the accumulation in moraines.

Some modification of the thickness of the drift occurred in the large area covered by the expanded Lake Erie while the Wisconsin ice sheet was gradually receding from northern and northwestern Ohio. Waves and currents eroded and worked over the glacial material, some of which was shifted out to deeper water, making the drift cover thinner near the shore. In places the water removed the deposits from the buried divides or hills, exposing the bedrock. This is suggested by the thinness of the mantle rock on the buried uplands in the area immediately to the south and southwest of Lake Erie.

Unless a well record, unknown to the writer, indicates deeper deposits, the greatest thickness of glacial drift thus far found in Ohio (763 feet) occurs near Independence, south of Cleveland, in the buried valley of the preglacial and interglacial Cuyahoga which passes through the city of Cleveland. The floor of this valley lies 13 feet below sea-level. The greatest thicknesses in western Ohio, as indicated by well records, are those along the old Teays Valley. At St. Paris in Champaign County and at the London Prison Farm in Madison County the thickness of the drift is 530 and 524 feet, respectively, but in neither case was bedrock reached. The drift in the old Teays Valley is more than 530 feet thick, but probably not much thicker, as indicated by the record at Anna, assuming that location to be somewhere near the axis of the valley.

THE PREGLACIAL DRAINAGE

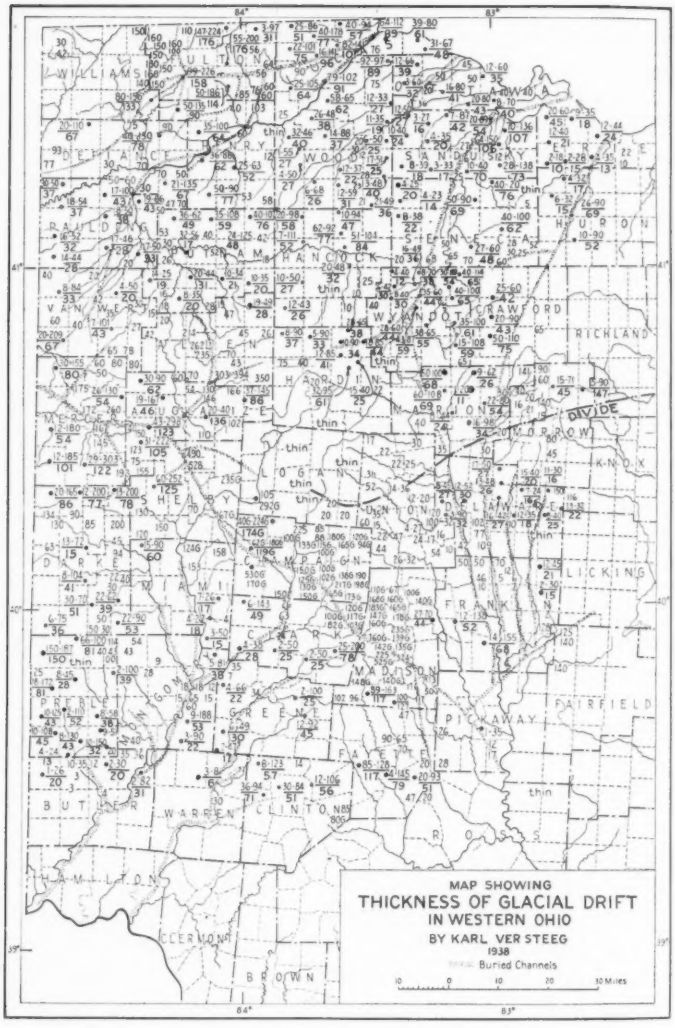
The preglacial Maumee, Portage, Sandusky, and Huron rivers were tributaries of a large stream which occupied the Erie lowland and flowed eastward. The preglacial Cuyahoga and Ohio rivers and other streams which drained the uplands to the south flowed northward to join this river.

The Teays had its source far to the east in the Appalachian region. Its course through western Ohio is indicated by a deep buried valley which passes through Pickaway, Madison, Clark, Champaign, Shelby, Auglaize, and Mercer counties (see Map 1). At the London Prison Farm in Madison County a well was drilled 525 feet in the glacial drift without striking bedrock. A short distance to the east the drill penetrated bedrock at 225 feet. Apparently an abrupt drop occurs here, indicating the presence of a deep valley extending in a northwesterly direction through Madison County. The drift cover is thin in the extreme northern part of Madison County, and the bedrock outcrops in places. But nearly all the well records show that the drill did not reach bedrock in the central portion of Madison County. Records up to 225 feet occur in the area immediately southeast of the junction of Madison, Clark, and Champaign counties. The thinness of the cover in the northern part of Madison and adjacent Franklin counties seems to indicate that the Teays Valley lies to the south, where the drift is comparable in thickness to that in Shelby County near the town of Anna. The buried valley continues through northeastern Clark and southwestern Champaign counties. In the latter, at the town of St. Paris, a well was drilled 530 feet without attaining bedrock, a depth which compares with the one at the London Prison Farm and at Anna. These wells are probably located on or near the axis of the buried valley of the old Teays, which extends to the Grand Reservoir in Auglaize County. From here it continues in a westerly direction through Mercer County and into Indiana. A study of the elevations beneath the drift cover in Miami County appears to indicate that the Teays River could not have turned southward here. Another stream flowed southward from a preglacial divide which separated it from the Teays. The latter, a large stream, could not have flowed through the smaller buried valleys which lead to the south.

The buried land surface in southwestern Ohio slopes to the southwest, and it appears that this condition prevailed in preglacial time. Under the circumstances the writer finds it difficult to visualize with W. G. Tight[3] a stream such as the Cincinnati River flowing northward to join the Teays in preglacial time. It is believed that

[3] "Southeastern Ohio and Adajcent Parts of West Virginia and Kentucky," *U.S. Geol. Surv. Prof. Paper 13* (1903), Pl. I.

MAP I


MAP SHOWING
THICKNESS OF GLACIAL DRIFT
IN WESTERN OHIO
BY KARL VER STEEG
1938
Buried Channels
10 0 10 20 30 Miles
WILLIAMS
FULTON
DEFIANCE
PAULDING
VAN WERT
PUTNAM
ALLEN
AUGLAIZE
MERCER
SHELBY
DARKE
MIAMI
HENRY
WOOD
SANDUSKY
SENECA
HANCOCK
WYANDOT
CRAWFORD
RICHLAND
HURON
MARION
HARDIN
LOGAN
CHAMPAIGN
CLARK
MADISON
UNION
DELAWARE
KNOX
LICKING
FRANKLIN
PICKAWAY
FAIRFIELD
PERRY
GREENE
FAYETTE
ROSS
BUTLER
WARREN
CLINTON
HAMILTON
CLERMONT
BROWN
DIVIDE

the buried upland of southwestern Ohio represents a dissected preglacial peneplain which sloped to the southwest and toward the streams. If the buried surface developed in interglacial times, the course of Tight's Cincinnati River can be explained as preglacial, when it might be assumed that the land surface sloped northward. It is not likely that the deep stage was sufficiently long for erosion to have produced a peneplain. The deep buried valleys in southwestern Ohio in Hamilton, Butler, Warren, and Montgomery counties are probably preglacial, deepened later during an interglacial stage.

GEOLOGICAL HISTORY

From a study of the buried preglacial topography the writer is able to make some inferences. In preglacial time the valleys of the larger streams in Ohio were broad and open, such as one would expect in an advanced stage in the cycle of erosion. Evidence has been presented in an earlier paper,[4] which indicates that in preglacial time the rivers of western and northern Ohio occupied broad valleys which were deepened considerably at a later time. It is the belief of geologists that in an interglacial stage, earlier than the Illinoian, the streams cut deep gorges in the preglacial valleys. That this is true is borne out by studies both of the valleys in the unglaciated portion of Ohio and of those buried beneath the glacial drift, such as the old Cuyahoga and the Teays. As the deep gorge of the Teays suggests that an interglacial stream flowed through it, in any discussion of this buried valley we must consider the probability that two streams occupied it, a preglacial one called the Teays, and a later one in an interglacial stage earlier than the Illinoian. The preglacial Teays[5] drained a large area in the Allegheny Plateau region in West Virginia and eastward, flowing in a northwesterly direction through Ohio and into Indiana were its course has been traced for some distance. The course of the interglacial stream is unknown, but the writer believes it may have flowed in a southeasterly direction into what is now the Ohio River, the waters escaping to the southwest as today.

[4] Ver Steeg, "The Buried Topography of Western Ohio," *op. cit.*, pp. 924–39.

[5] *Ibid.*, pp. 924–29.

RECENT LANDSLIDES IN SALMON CREEK CANYON, IDAHO

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University of Arizona

The Buhl landslide area which has been called various names, such as, "Buhl Sinking Area," and "Robertson's Sinking Farm," is approximately 7 miles west of Buhl, Idaho, on the east margin of Salmon Creek Canyon, about 5 miles south of its junction with the Snake River. The writer visited the area early in September, 1937, at which time most of the movements had ceased, but some adjustments were still in progress. Pictures of the area at various stages of the movement, and testimony of local people helped the writer to interpret the sequence of events.

Early evidence of movement was the formation of cracks both on the canyon floor and on the summit to the east. They had been noticeable in the canyon as far back as three years ago. Because of these cracks, the farm land involved in the subsidence area had been abandoned more than a year.

The canyon at this point is not symmetrical, the west wall being very precipitous with a large talus slope extending from the creek's edge to within about a hundred feet of the top. Lava flows that protrude in places closely underlie this talus (Fig. 1). Extending from the creek's edge eastward for several thousand feet is a broad expanse of broken lava which stands well above Salmon Creek and rises eastward to within about two hundred feet of the rim. From this point the east wall rises vertically (Fig. 1).

The writer believes that this mass of broken lava lying within the canyon is the result of phenomena similar to those which have just taken place. The recent landsliding occurred because Salmon Creek, by gradually deepening its channel, removed material from the canyon floor which supported this broken mass. Gravity, acting on the then unsupported material, caused it to move toward the river. The collapsing east wall (Fig. 2) must have exerted a force against

the landslide mass, so that $A+B$ equaled the force acting to start the landslide. However, after movement started, the landslide mass, including a portion of the rim, moved of its own weight, and the space it formerly occupied was refilled simultaneously by the collapsing wall, producing a subsiding effect (Fig. 3).

Early stages of movement were a development of cracks in the lava within the canyon, followed by a gradual formation on the east rim of arc-shaped breaks concave toward the canyon (Fig. 4). As the fissures near the edge widened, others formed behind them. The broken mass of lava in the canyon and a portion of the canyon wall which moved with it slowly continued sliding westward, and almost simultaneously, the weak wall of the canyon began subsiding and crumpling behind it. The landslide continued moving until its front had pushed against the west wall of the canyon. This partially filled the creek, forcing it out of its old channel. The damming effect created rapids and small ponds (Figs. 5, 6). Subsidence continued until the

FIG. 1.—Panoramic view of Salmon Creek Canyon looking south. (*A*) At extreme left subsidence area showing collapsed canyon wall. Note that part of the wall is still standing although it has moved westward with the landslide. Also note, behind the slide in the subsidence area, the blocks of lava separated by deep cracks. (*B*) In center foreground the broad expanse of broken lava, within the canyon walls, that slid toward the river. (*C*) Salmon Creek. (*D*) Steep west wall of the canyon, showing talus slope with protruding masses of the underlying lava flows.

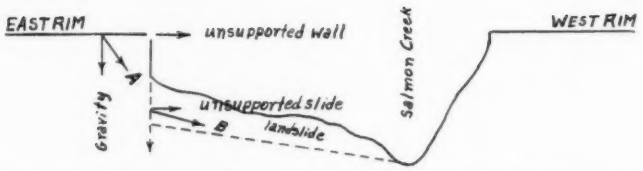

FIG. 2.—$A+B$=force acting to start the sliding of the mass into the creek. B= force acting to continue movement. The east wall crumpled loosely behind the slide.

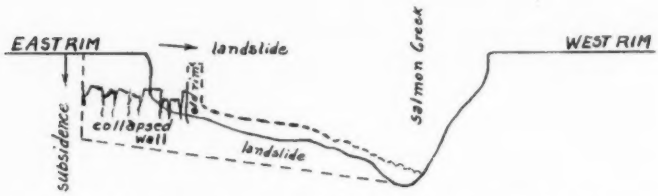

FIG. 3.—Full line shows the old outline of the canyon. Dashed line shows new canyon outline after landsliding and slumping.

FIG. 4.—Photograph of east margin of the subsidence area. In the foreground are seen the arc-shaped breaks concave toward the canyon. In the middle is one of the larger sinking blocks. At the extreme right is a portion of the old canyon wall which moved with the landslide and which has subsided little.

FIG. 5.—Photograph (retouched) looking northeast from west rim of canyon at landslide area. In the foreground are (*A*) ponds or small lakes and (*B*) rapids caused by the damming of Salmon Creek. In the background (*C*) is the broken lava landslide mass. White areas (*D*) are the newly exposed surfaces. Newly exposed scarp (*E*) on east wall of canyon.

FIG. 6.—Photograph looking north (downstream) at the landslide that has partially dammed Salmon Creek. (*A*) Small lake. Brush at edges are the tops of willow trees that grew along the bank before being submerged. (*B*) Old channel that has been elevated. (*C*) Position of new channel. (*D*) West wall of canyon. (*E*) Front of landslide.

several acres involved were over a hundred feet below their original level. This mass, which had sunk from the start more or less as a unit, began to break up into blocks separated by wide and deep cracks. A large portion of it collapsed into a mass of broken rock (Fig. 1).

Collapse into open caverns or subterranean rivers, as has been suggested, was not responsible for the phenomena. The portion of

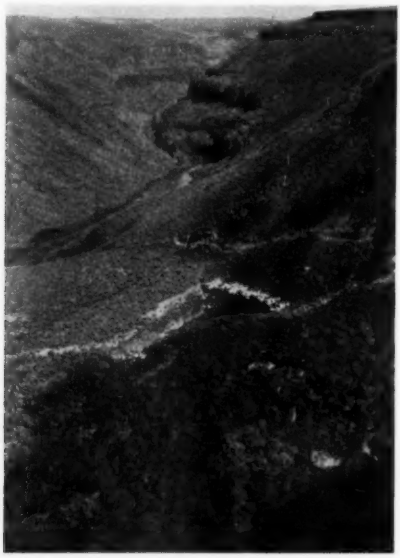

FIG. 7.—Photograph looking north from the east rim at a small landslide at the northern end of the disturbed area. The pond behind is probably derived from seepage water from the irrigated tract to the east. Cf. with Figs. 5 and 6.

the canyon wall that moved intact with the landslide mass was still standing almost at its original elevation, although it was one hundred or more feet west of its old site (Fig. 1). Landsliding and slumping are so evident that it is not necessary to postulate any other cause (Figs. 5, 6, 7). The subsidence was the adjustment of a weak section of the canyon wall that could not stand at its height above the canyon floor without support. Small strips around the margin of the

collapsed area are still falling and will probably continue to do so for some time to come.

A small landslide (Fig. 7) has slumped westward toward the river, and, except in size, is very little different from the one just described (Figs. 5 and 6 for comparison). Behind the landslide a pond of seepage water has formed.

It has been suggested that seepage water from the Twin Falls irrigation tract is responsible for the movements, by weakening the rock and acting as lubricant along friction lines. Seepage water entering the canyon may have accelerated the movements. However, elsewhere in the canyon are similar old landslides and slump areas that certainly were there long before any irrigation began. The Twin Falls tract has been under irrigation not over fifty years.

In December, 1937, I was informed by Ormond Thomas of Buhl, Idaho, that new slides have developed on the west wall of the canyon opposite the southern end of the slide area. This tends to substantiate my belief that the movements are landslides caused by the depth of the canyon, and that seepage water is of no importance in causing the movements. No seepage water enters the canyon from the west wall.

SUMMARY

Salmon Creek, by deepening its channel, removed material which supported a large mass of broken lava. This mass, which had partially supported a weak section of the canyon wall, started moving, and as it slid away the canyon wall began to crack and its outer portion moved forward with the landslide. The subsidence area then collapsed and sank into the space formerly occupied by the slide. Rapids and small ponds were formed in Salmon Creek by the slide material. Seepage water may have acted as a lubricant along friction planes after movement began, but it does not seem to have been a necessary factor in starting the slide.

EDITORIAL

In February, 1938, appeared the first number of the *Journal of Geomorphology*, edited by Douglas Johnson and Henry S. Sharp and published by the Columbia University Press. The new *Journal* starts vigorously; the policy of its editors, expressed and in operation, imparts a refreshing tone and spirit which permeate the whole number. The inaugural issue is in every way a very satisfactory one; may its high level of achievement be maintained and its success continue. The *Journal of Geology* welcomes into the family of geologic publications its youngest sister, the *Journal of Geomorphology*.

REVIEWS

Introduction to the Study of Minerals. By AUSTIN FLINT ROGERS. 3d ed. New York and London: McGraw-Hill Book Co., 1937. Pp. xviii+626; figs. 729. $5.00.

This edition differs from the two earlier ones in that it is of full octavo size, involving an increase in page size of one and two inches and in format length of one inch, and the addition of about one hundred and fifty figures and one hundred pages of text, most of which are devoted to morphology (thirty-seven pages) and mineral description (fifty-four pages). Two hundred minerals are described in the first edition (1912), 175 in the second (1921), 222 in this. The second edition starts with chemical properties, the first and third with morphology. The third edition resembles the first more than the second in other ways too. Thus the new book devotes a section to the stereographic projection and describes crystal systems beginning with the orthorhombic. Unfortunately, adequate discussion of crystal habit and growth is missing from both later editions. The determinative table based on chemical tests is omitted from the new edition, but the common tests of "blowpipe analysis" are presented, in addition to which a new short (seventeen-page) section treats microchemical analysis.

On the whole the new book is a great improvement and should be very useful as a text in beginning courses at the university level. While there is a twenty-page section devoted to space-lattices and the methods of X-ray analysis, the major developments of the last twenty-five years, based on roentgenographic studies, are not well covered in the sections on isomorphism and polymorphism, mineral formulas, and classification (especially silicates). The failure to treat optical and other properties as variables dependent on chemical composition, with suitable explanatory diagrams for at least the more important series, is also to be regretted in a text of this type. Elements of crystallization are omitted in many cases. Among minor points may be mentioned the classification of ice as a sedimentary rock; hail and analogous atmospheric forms are sedimentary, but glacial ice is metamorphic and young sea ice is igneous.

The headings under mineral descriptions are differentiated by boldfaced type, a desirable feature that has been retained. Moreover, head-

ings covering microscopic (including microchemical) tests, alteration products, and derivation and pronunciation of names have been added. German and French equivalents are also given. An Appendix contains a listing of minerals according to elements present.

D. JEROME FISHER

The Quaternary Ice Age. By W. B. WRIGHT. 2d ed. London: Macmillan & Co., Ltd., 1937. Pp. 478; pls. 23; figs. 155. $9.00.

In 1914, when the first edition of this work appeared, it was the only comprehensive synthesis in English of an already bulky literature on the Ice Age. The present edition has been revised and amplified to keep in step with the progress of research. For example, the reader will here find a thorough analysis of recent archeological studies tending toward a clarification of the problems of European correlation.

An introductory discussion of glacier mechanics and the erosion and deposition performed by glaciers includes a summary of important determinations achieved through the study of varved clays. The glacial history of the British Isles, the Alps, Northern Europe, and North America is taken up in systematic fashion, with Britain naturally receiving the lion's share of attention. Associated evidence on the floral, faunal, and climatological records in each area is fully discussed. Particular treatment is allotted to "The Loess," "Quaternary Mammals," and "Quaternary Man" in later chapters. Among various "Theories of the Ice Age," for the most part briefly disposed of, Croll's astronomical theory, with modifications by various authors, is developed at some length as best explaining the known sequence of events.

The latter part of the book deals with the question of oscillating shorelines. Dr. Wright in 1914 first proposed interaction between eustatic changes of sea-level and isostatic recovery from ice load as the key factors in this problem. This theory, amply supported by evidence from both sides of the Atlantic, he now names the "isokinetic theory."

Brief discussion of botanical researches in postglacial plant migrations and climatic variations, rounded off by a summary of the present state of our knowledge concerning the Ice Age, concludes the volume. The Bibliography is concise, thorough, and up to date. Careful indexing and a clear marginal summary render easy the running-down of any particular topic in this very valuable reference work.

WILLIAM F. READ

"Lower Mississippi River Delta; Reports on the Geology of Plaquemines and St. Bernard Parishes (Louisiana)." By RICHARD JOEL RUSSELL, HENRY V. HOWE, JAMES H. MCGUIRT, CHRISTIAN F. DOHM, WADE HADLEY, JR., FRED B. KNIFFEN, AND CLAIR A. BROWN. Edited by RICHARD JOEL RUSSELL. *Louisiana Department of Conservation Geological Bulletin 8.* New Orleans: Louisiana Geological Survey (Research Division), November 1, 1936 (distributed May, 1937). Pp. xiii+454; figs. 36; frontispiece; cover map; pls. 17.

This book is the first comprehensive study of the lower Mississippi delta. Its conclusions lead the senior author to offer modifications of current conceptions of the origin of geosynclines, the stability of the earth's crust over small areas, the structure of deltas of the coastal plain type, and the origin and classification of meanders. To the reviewer this study seems to prove its thesis that the Mississippi delta is now tilting toward the gulf with gradual submergence of its protuberant portion except where locally maintained above sea by alluviation. These conclusions are in agreement with his own work on the coastline of Texas and northern Mexico.

The separate reports included in the volume are: "Physiography," by Russell, 199 pages; "Salt Domes," by Howe and McGuirt, 79 pages; "Petrography" (of two subdeltas and extraneous pebbles on Chandeleur Islands), by Dohm, 64 pages in two reports; "Archaeology," preliminary report on Indian mounds and middens, by Kniffen, 16 pages; "Vegetation" of mounds, middens and marshes, by Brown, 18 pages; "Recent Mollusca," by Hadley, 4 pages; "Bibliography," by Russell and Dohm, 42 pages; and "List of Maps," by Dohm, 18 pages, two most extensive lists; a detailed "Index," 14 pages.

Some main conclusions of the book are briefly noted in the following paragraphs:

A delta is discussed as an alluvial region between the branching distributaries of a river. The deltaic plain is the wider alluvial area over which, by shifting of delta positions, the distal deposits of the stream have been spread. Deposition in a delta occurs in the active subdelta. "Foreset beds" seem to have no definite place in the Mississippi delta, the traditional textbook conception of delta structure not being supported by this investigation.

Abandoned subdeltas are marked by seaward tilt, submergence, and receding shorelines. The deltaic sediments sink under accumulating load. In the early stages of tilt the beach formed along the subdelta shores upon its abandonment by the river may be maintained to and above sea-level

while the remaining surface of the seaward areas becomes submerged. This beach may be arcuate in outline. The beach thus becomes an offshore bar formed during submergence. Later the bar retreats to land, accompanied by straightening of the shoreline. These are features described for the modern delta of the Mississippi in St. Bernard, Plaquemines, and adjacent parishes. The delta plain stretches along the entire coast of Louisiana inland from the active delta and the coastal marsh of southwestern Louisiana previously described by Howe and Russell in *Bulletin 6* of this series.

The gulf-coast geosyncline, previously described by several writers and well known to the petroleum geologists, whose thousands of wells have strongly indicated its presence, is composed of Tertiary sediments which reach a maximum estimated thickness of some 35,000 to 45,000 feet or more in the lower Mississippi delta. Its axis runs along the coast of Louisiana and Texas as far, at least, as Corpus Christi. The sinking of the deltaic sediments of the Mississippi and its predecessors is thought by Russell to have dominated in the production of this geosyncline. The Mississippi deltas with those of other gulf-coast streams formed a great deltaic complex, product of the wasting of the central area of the continent. Uptilt in marginal land areas closely bordering the modern delta offsets late sinking in its coastal portion.

Russell's evidence for subsidence and seaward tilt of the delta includes marginal lagoons, partly submerged marshes, and rapid wasting of abandoned subdeltas which occur too extensively to be explained by marine planation unaided. Also the gradient of a former main channel of the river in the recently abandoned St. Bernard subdelta is much higher (0.7 ft. per mile) than that of the modern stream in the lower delta. Indian mounds and middens and natural levees are found, some partly, some wholly buried in marsh deposits and showing oxidized soils. In at least one of these occurrences local settling (2 ft.) seems to Russell to be plainly distinguishable from the greater (7 ft.) areal subsidence.

In his discussion of current views strongly opposed to his hypotheses of subsidence and tilt and of subsidence under load Russell cites, among others, the following cases: Barrell thought the Nile delta was an excess load supported by the strength of the earth's crust, but the conception of delta structure current at that time and upon which he relied is believed by Russell to be erroneous. He also finds Barrell's calculations to have been supplanted by those of Nansen. Gulliver and Douglas Johnson have described offshore bars as typically the product of "emergent coasts." Following this interpretation, authors have introduced into coastal his-

tory an episode of emergence where offshore bars were found. Russell cites instances of such a "hypothetical" episode having been introduced where he finds abundant evidences of submergence. The reviewer notes that Douglas Johnson specifically stated that the "initial profile" and "history of development" would be the same for a shoreline of emergence on a "young, undissected alluvial plain" as for a typical shoreline of submergence.[1] Russell thinks the concepts of advancing and retreating shores are more useful than those of emergence and submergence in the discussion of shorelines.

Russell questions the adequacy of current conceptions of meanders and meandering. His work and that of Melton[2] seem to the reviewer to indicate that a thorough revision of meander terminology and classification is needed. From such a work a revision of our ideas of meander formation is likely to follow. Russell contributes much illuminating thought to the subject. He finds a meander pattern characteristic of tidal courses established in homogeneous materials in partly submerged lands, but seems not to show that the process of meandering continues where the loops are once formed. This phase of meandering streams is not fully discussed. Russell shows that straight courses are characteristic of the distributary channels of this river in the active subdelta, but meander loops characterize it farther upstream. He suggests that meanders may not form where there is only a small percentage difference between normal high and low stages in a river, but may be abundant where this difference is large. Turbulence theories are studied in relation to meander formation.

The physiographic study and the far-reaching conclusions presented seem to the reviewer to warrant a much fuller exposition of the underlying data and much more extensive factual and diagrammatic illustration than are given in the book. He also regrets that opposing theories are not confronted in detail in respect to the Mississippi delta. Had they been so applied, the author's processes of reasoning in the elimination of such opposing ideas would be more readily followed. The reviewer also believes that, in so doing, some data offered by the author as evidence of subsidence might have appeared equally well to support coastal stability. For example, the loss of land in the Chandeleur Sound-Isle au Pitre area recorded by recent maps is not convincingly shown to require subsidence. The "soupy" nature of the marsh composing the coastal lands, as

[1] Douglas W. Johnson, *Shore Processes and Shoreline Development* (New York: John Wiley & Sons, 1919). Pp. xvii+584, figs. 149, pls. 73. See page 201.

[2] Frank A. Melton, "An Empirical Classification of Flood-Plain Streams," *Geog. Rev.*, Vol. XXVI, No. 4 (October, 1936), pp. 593–609, figs. 15.

has been pointed out by Donald C. Barton,[3] might be thought to permit rapid shoreline retreat behind the protecting Chandeleur Island arc under coastal stability with the preservation of the grain of the country and without shoreline straightening.

To the reviewer the single bit of evidence of tilt presented by the steepened gradient of the abandoned main channel of the Mississippi in the St. Bernard subdelta—the Bayou la Loutre—dominates Russell's entire marshaling of facts in support of the subsidence-and-tilt hypothesis. Once this is accepted as establishing tilt, then the convergence of supporting evidence from such items as regional hydrographic patterns of subsidence, shoreline retreat, and buried mounds, middens, and other cultural objects acquires an importance which they, individually, might not be thought to possess. The book is written in simple, effective English. The associated studies supporting the physiographic paper seem to be well executed. Typographical errors were not discovered. Some of the maps were not so lettered as to stand the heavy reduction which they have suffered. Place-names are hard to find without the use of the Index, and the lack of a general map of the area is keenly felt by the reader. A fairly suitable sheet for this purpose is the United States Army engineer's map of southern Louisiana, scale 6 miles to 1 inch, price one dollar. The 1937 edition of this map is expected soon.

It is to be hoped that this group of investigators will, some day, give us, in the light of their mature judgment, a fully illustrated, detailed account of the entire Mississippi delta and its adjacent deltaic plains.

The reviewer, from his studies of the adjacent coasts of Texas and Mexico, finds himself in rather full accord with the major conclusions of the report so far as his study of it has gone. The book is a "meaty" one and not to be assimilated rapidly.

W. Armstrong Price

The Universe Surveyed. By Harold Richards. New York: Van Nostrand Co., Inc., 1937. Pp. 722; figs. 94. $3.50.

Dr. Richards' book attempts to interpret for the novice some underlying principles of the physical sciences. An Introduction sets the stage: ponders the aspirations of science, analyzes its methods, defines its limitations. The book is divided into four main units which deal with (1) astronomy, (2) the nature of matter and energy, (3) science in modern technology, and (4) geology.

The study of a basic concept, gravitation, introduces astronomy. Its

[3] Personal communication.

history is traced from Aristotle to Newton; its universal application is found in many familiar phenomena of earth and sky; dire consequences are foretold in the event of its cessation. A very few pages are given to the origin of our solar system, but in an Appendix fuller astronomical data, impressively presented, will be found. In attacking the nature of energy and matter, the first move is to discover historically how heat, one form of energy, was placed on a measurable basis, after which it is not hard to see how the quantitative relations involved in transformations of energy were mastered. The next step is to explore the nature of energy transformation, a problem requiring consideration of the atomic nature of matter. Once the relation between heat and mechanical energy is grasped, the way is open to discussion of two other forms of energy, radiant and electrical, which introduces us to still more basic aspects of matter. Practical applications of science raise the recurrent question of social responsibility. The unit on technology covers the sources and utilization of energy—food, fuel, and electricity; of raw materials—metallic and nonmetallic; also communication and its foundations, optics and acoustics. The geological portion is brief: a few suggestions on the operation of geological processes; some of the more prominent events in earth history; and, what is more important, the posing of some of those fundamental questions about the earth that still puzzle the geologist. In conclusion, a glance over the frontiers of science carries home the realization that philosophical readjustment is the necessary accompaniment of scientific advance.

WILLIAM READ

Structural Petrology. By H. W. FAIRBAIRN. Kingston, Ont.: Queen's University, 1937. Mimeographed. Pp. 150; figs. 54. $2.00.

Recognizing the need for an English treatment of the growing science of fabric analysis, Dr. Fairbairn in 1935 prepared a set of mimeographed lecture notes entitled *Introduction to Petrofabric Analysis.* This was unbound, meagerly illustrated, and admittedly the material was not in a finished state. The present book is a revision, well bound, with more illustrations, incorporating much of the recent work on fabric analysis, and with an Appendix on plastic deformation of several types of crystals. Perhaps the biggest change is the inclusion of a detailed geometric analysis of the properties of the strain ellipsoid and the development of a hypothesis of rupture.

The reviewer finds the former title more appropriate to the text, as it is a brief introduction, which must omit much of the material already in print on the subject of petrofabric analysis. Also, it makes no attempt to

cover the whole field of structural petrology, including only cursory mention of any of the field data.

This manual should serve as a guide through the first stages of microfabric analysis, such as collecting oriented specimens and using the universal stage. Because of the inherent complexity of the subject, however, the student will soon find himself faced by problems to which he will find no answer in Dr. Fairbairn's book. For example, little mention is made of the difficulty of sampling in order to get a true statistical picture of the rock—the problem of dealing with inhomogeneity, either microscopic or megascopic.

Since the first days of cleavage observations there has been controversy as to whether cleavage forms normal to the direction of maximum pressure (load metamorphism, axial-plane cleavage, etc.) or inclined to it on shear planes. Fabric analysis puts a powerful tool into the geologist's hands, enabling him to acquire more data bearing on this problem. Fairbairn has attempted a fabric classification representing these two types of cleavage formation. In so far as this classification is found to coincide with field evidence, it will be very helpful, both practically in determining the structure of a region and theoretically in furthering the understanding of the mechanism of formation of cleavage planes.

In common with many other workers in the field of *Gefügekunde*, Fairbairn considers the fabric analyses proof that plastic flow occurs in rocks mainly as a result of crystal slip and twinning. To quote his definition: "Plastic deformation is that deformation beyond the elastic limit of a substance which occurs by gliding in the crystal planes, the continuity of the deformed structure being retained" (p. 39). Fabric analyses certainly show that minerals in metamorphic rocks are oriented to a degree unrealized before the development of statistical universal stage methods by Sander, but the mechanism producing that orientation is still very poorly understood. The reviewer believes that more consideration should be given to the possibility of deformation by intergranular movement and by recrystallization.

The theoretical treatment of the mechanism of rock deformation and fracture is disappointing. A new hypothesis of rupture is developed—the planes of "uniform distortion of the strain ellipsoid." This hypothesis is based on a purely geometrical argument, not correlated with experimental evidence, field data, or physical theory. Fairbairn assigns a mystical significance to "uniform distortion."

There is a recurring tendency to accept uncritically the contents of various scientific papers—an example is the excerpt from Winchell's paper on the statistical evaluation of petrofabric diagrams, which, while serving

as an admirable stimulus to the mathematical evaluation of diagrams, is yet in such an incomplete stage as to be misleading to one who attempts to apply it.

The book is well printed, well proofread (in contrast to most mimeographed efforts), and, in spite of some errors which appear glaringly to a research worker in this field, will serve as an introduction to petrofabric analysis. The bulk of the material is still the work of Dr. Bruno Sander, and the more advanced student must go to his *Gefügekunde der Gesteine* for the most complete treatment of the subject.

DAVID GRIGGS

Lehrbuch der Geologie, Teil III: *Geologische Länderkunde* (*regionale Geologie*), Parts I–VII. By F. X. SCHAFFER. Leipzig & Wien: F. Deuticke, 1930–37.

The third volume of Schaffer's textbook contains a succinct geological description of the surface of the earth. Dr. Schaffer visited on repeated excursions a great many of the countries he treats in his book and discussed the essential geological problems on the spot with the leading authorities. His work is now nearly completed.

In the last two parts he sets forth a new and original explanation of the structure of the Alps and other fold-mountains, strongly contrasted with the theories of nappism, which were always looked upon with some skepticism by many Austrian geologists. According to this view the Mediterranean region was divided in Mesozoic time into two fundamentally different parts, which the author calls the Hesperian province (in the west) and the Tethydian province (in the east). In the former, the sediments from the Permian to the Lower Cretaceous, formed in more or less closed basins, are poorly developed, often metamorphosed, fossils are scarce, and the tectonic disturbances are "germanotypic," at least in the more extensive southern and western parts of the province. In the Tethydian province the sediments are truly marine, very thick, rich in fossils, and much disturbed by tectonic movements.

The following countries belong to the Hesperian province: the folded mountains of North Africa, the Betic Cordillera, the Balearic Islands, the borderland of the Iberian Meseta, the Pyrenees, the Apennines, and the Western Alps. The Apennines in the geographic sense are not a geological unit. They contain the ruins of the Mesozoic Paleoapennines, partly buried under the Flysch-Apennines with bilateral tectonics brought about by sliding.

The sediments of the Western or Hesperian Alps were deposited in several elongated troughs separated by Hercynian horsts. One of these

basins had a freer connection than the others with the geosyncline of the Eastern Alps. The sediments of a more Tethydian pattern laid down in it were transformed by subsequent disturbances into the Préalpes and the klippes of Switzerland, which, according to Schaffer, are parautochthonous, not transported from the south. Another trough with sediments resembling to some extent those of the Eastern Alps was the Penninian zone, situated more to the south. The crystalline massives of the Western Alps were moved toward the west and north. They were, however, not overthrust upon younger strata. While sliding outward over plastic, deeper layers of the earth's crust, they compressed and folded the younger sediments lying between and in front of them.

The stratigraphic classification of the more typical sediments of the Hesperian province is still a very unsatisfactory one. The "Casannaschiefer," "Bündner Schiefer," "Schistes lustrés," etc., are facies of metamorphism, not stratigraphic units. Some of the rocks called Verrucano and supposed to be Permian are in reality of Lower Cretaceous age.

The boundary between the Western and Eastern Alps, the so-called "line of the Rhine," was predetermined by the shelf between the Hesperian basins and the open Tethydian sea. At present it is a zone of enormous disturbances. The continuation of this boundary runs along the western border of the Lombardian plain and along the eastern foot of the Apennines. At the latitude of Naples it bends westward to include southern Italy and Sicily, which are Tethydian.

The Mesozoic sediments of the Eastern Alps are typically Tethydian in the northern and southern zones, but more epicontinental in the central zone. Metamorphism is slight in the Paleozoic rocks of the outer zones and absent in the Mesozoic ones. Fossils are plentiful and well preserved. Exact stratigraphic correlations are therefore possible.

In Mesozoic time the Central Alps lay more to the south than at present. While drifting northward they compressed the Northern Alps and caused the formation of several minor thrust masses. The Northern Alps are not overthrust over the central zone. The author denies the existence of the "windows" of Lower Engadin, of the Tauern, and of the Semmering.

Dr. Schaffer's views will certainly not meet with unanimous approval among Alpine geologists. In any case they are based upon a knowledge of those parts of the world where mountain chains seem at present to be in the process of building. For this and other reasons they deserve our attention and a critical discussion—which, of course, would greatly exceed the space available for this abstract.

JULIUS PIA

Vienna

Handbuch der regionalen Geologie, Heft 29: *Mittelamerika*. By KARL SAPPER. Heidelberg: Carl Winters Universitätsbuchhandlung, 1937. Pp. 160; pls. 11; figs. 15. Rm. 23.

The present publication constitutes the twenty-ninth in a series, which, when completed, will outline the geology of the entire world. It is written by a scholar whose researches in the field of Central American geology have been outstanding. Dr. Sapper has attempted to synthesize the available material, not only from scientific sources, but from explorers' accounts, mining and oilfield data, and engineering reports. Pains have been taken to give, where possible, the original source of all data used in this paper, which will, therefore, serve as a reliable guide to more detailed study.

The presentation falls into two main portions. The first deals with broad outlines of physiography, stratigraphy, petrography, tectonics, and geologic history for the region as a whole. The second covers in more detail the features of eight major orographical subdivisions, including the Isthmus of Tehuantepec and Yucatan on the north. In the earlier portion volcanic and seismological phenomena of the eruptive belt flanking the Pacific Coast are amply dealt with; problems of correlation are discussed; and an attempt is made to link the Cretaceous and Eocene histories of North and Middle America on paleographical diagrams. Discussion of the eight smaller units centers about a corresponding series of eight geologic maps, in black and white, which represent a synthesis of the best data available on each unit. Additional information concerning paleontology, character of sediments, structural relationships, etc., is presented in the text. Naturally, the amount of material on different areas is extremely variable, Panama and Nicaragua, for instance, having been thoroughly studied in connection with canal projects, while elsewhere large areas remain practically unknown.

The paper closes with a very brief summary of soils and mineral resources.

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Geology of Western Quruq Tagh, Eastern T'ien-Shan: Reports from the Scientific Expedition to the North-western Provinces of China under Leadership of Dr. Sven Hedin, III: 1. *Geology*. By ERIK NORIN. Stockholm: Bokförlags Aktiebolaget Thule, 1937. Pp. 194; figs. 19; pls. 43; 3 plates of sections and 2 maps in pocket.

The Tarim Basin of central Asia is open toward the east and connects with the immense plains of the Gobi Desert. Toward the east, however, the width of the basin diminishes as the desert ranges of the Quruq Tagh come in en echelon on the north. These ranges represent a spreading and

dying-out of the great Tien Shan system eastward and southeastward. Their geology is the subject of the present splendid volume by Norin based upon the field work by the Sino-Swedish expedition of 1928–30. An area of about 3,500 sq.km. was mapped, most of which is occupied by ancient gneisses and sub-Cambrian and Cambro-Ordovician sediments and eruptives.

Upon a basement complex of para- and ortho-gneisses rests the Bayisi sedimentary formation, which, in turn, is overlain by the Altungol formation, consisting mainly of felsitic effusives and pyroclastics together with quartzites, conglomerates, and slates. These grade upward into the Tereeken formation of more largely argillaceous and calcareous sediments with an abundance of ice-drifted boulders and pebbles in certain horizons. Above the Tereeken is the Yukkengol formation of slates with some quartzite and interstratified limestones. In close association with the younger members of the Yukkengol formation, though disconformably, are fossil-bearing marine sediments of Upper Cambrian age, to which has been given the name Torsuqtagh formation. These rest on a coarse boulder bed probably of tillitic character, which forms the uppermost horizon of a series of thinly bedded calcareous shales with limestone layers. The whole succession of formations from the basal gneisses to and including the upper boulder-bearing bed is grouped together under the name of the Quruqtagh series, an aggregate of several thousand meters of geosynclinal sediments. The upper portion of the Quruqtagh series is either of Proterozoic or Cambrian age. The boulder bed at the base of the Upper Cambrian Torsuqtagh formation strikingly resembles the sub-Cambrian tillite of east Greenland and northern Norway.

The general stratigraphy is compared critically with that of various other regions. Considerable parallelism is found between the sub-Cambrian and Cambrian sequence of the Quruq Tagh area and that of east Greenland, Spitzbergen, northern Norway, south-central Siberia, central China, South Australia, and South Africa, though the oldest fossiliferous beds overlying the sub-Cambrian tillite range from Lower to Upper Cambrian in these different regions. A feature common to most of these occurrences of sub-Cambrian or Cambrian glacial deposits is the great amount of volcanic material among the boulder beds, which inclines the author to the hypothesis that volcanic dust in the atmosphere may have been an important factor in causing the glacial climates.

The volume is illustrated with many excellent plates portraying the geomorphologic features of the region, the igneous and metamorphic rocks from photomicrographs, and other prominent elements of the geology.

R. T. C.

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